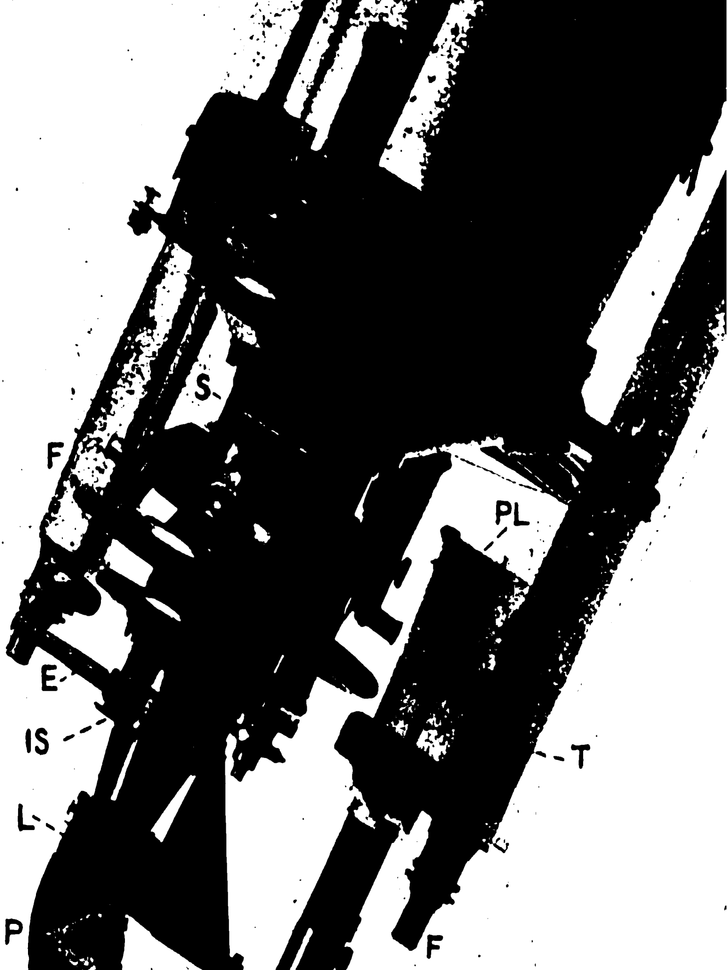
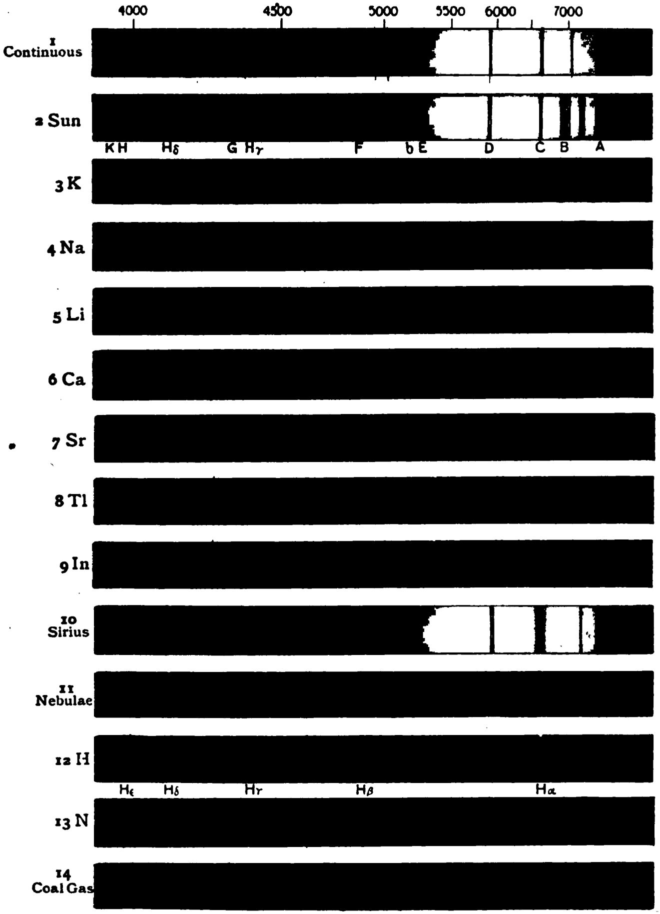


The spectroscope and its work

H. F. Newall



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b E
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3 K
4 Na
5 Li
6 Ca
7 Sr
8 Tl
9 In
10 Sirius
11 Nebulae
12 H
Hε
Hδ
Hγ
Hβ
Hα
13 N
14 Coal Gas

Manuals of Elementary Science

THE SPECTROSCOPE AND ITS WORK

BY

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PREFACE

To any one, who takes up this primer with the hope of getting to know something of the work of the spectroscope, I would point out that it is at best an attempt to describe some of the elements of a subject wherein the guiding phenomena are wonderfully beautiful, but also complicated in spite of their seeming simplicity. In such a case verbal descriptions may be misleading. I am almost tempted to strike out the reiterated title printed on every other page and to substitute the words "Study the phenomena themselves." The book will have missed its point, if it does not stir up the reader to wish to see for himself.

To those who use the book as a help in teaching, I should be grateful for all hints that would tend to remove error and obscurity from it and make it more serviceable for their purpose.

I wish to express my obligations to the Royal Society, the Royal Astronomical Society, Sir Norman Lockyer, Major E. H. Hills, Professor G. E. Hale, Professor E. E. Barnard, and the editors of the *Astrophysical Journal*, for permission to reproduce plates in illustration of the subject. These plates will be found at the end of the book.

Professor A. M. Worthington has rendered me great help by suggestions made after reading the proof sheets of all the earlier chapters of the book. I am glad to have this opportunity of thanking him.

H. F. NEWALL.

June 1910.

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INTRODUCTION

White is always regarded as the emblem of purity. Ruthless science tears it to pieces and convinces us that it is the most complex of all the colours in Nature.

The red of a tulip, the green flash of an emerald, the purple of a violet, all seem to give us something *more* than the whiteness of the lily, such slaves are we to ideas gained from laying on paint. The truth is, they all give us much less. The lily gives back all the light that falls upon it; the tulip, the violet, and the emerald, each lighted by the same sunlight, gives back only a small part and suppresses all the rest; not one of the three adds anything to the sunlight which makes them visible; each abstracts a great deal from it and suppresses it, and shines with but a small part of the light that falls upon it. Hence, in the evening, when the daylight dies away, the white lilies, giving back all the light that falls upon them, seem to stand out visible long after the gayer flowers have disappeared in the dusk.

The world is gaily coloured, because a complex light falls upon complex structure and is apprehended by a complex eye and brain. One hardly knows which excites the most wonder, the complexity of the light, or the varied minute structure that makes different surfaces able to absorb special components in the light, or the marvellous structure and processes in the eye and brain that enable us to perceive the differences. Perhaps more wonderful still is the

fact that it has been given to men to learn so much about the mechanism concerned in each case.

Sir Isaac Newton's discovery that sunlight is composite and capable of being split up into a number of different components, is the true origin of all the later developments in which the spectroscope has proved to be the key to mysteries of the greatest variety. How great that variety is may be seen from a mere enumeration of some of the uses to which the spectroscope has been put:—

The complexity of light has been discovered.
An unmistakable characteristic for each chemical element has been found.
New chemical elements have been discovered.
The composition of the sun and stars and nebulæ has been probed.
The velocity of the stars has been determined.
The velocity of the sun in space has been deduced.
The periods of rotation of the sun and of some of the planets have been determined.
Magnetic storms on the surface of the sun have been detected.
The development or life-history of celestial bodies is being studied.
New complex systems of suns have been discovered.
The vibration of molecules has been investigated.
The study of the nature of electricity has been helped.
The relation between matter and ether has been studied.
The temperature of incandescent bodies and even of the sun has been gauged.
The manufacture of steel has been facilitated.
The circulation of the blood has been studied.
Some of the processes in plant-life have been investigated.

Just as a noise—such as the shouting of a mob—

is a jangle of sounds which can be analyzed into pure tones, each with definite pitch and loudness, so light—such as that of a candle—can be resolved into various simple components which can be separated from one another. White sunlight when analyzed is found to consist of an infinite variety of pure components, each of which is light of a pure colour incapable of further resolution.

The spectroscope is the instrument which has been devised for analyzing the light that comes from any source. It is the object of the spectroscope to show what various kinds of coloured light exist as components in the light emitted by any source of light. Its method of action is such as to spread out the components side by side, so that they are visible at a glance. What is seen in the field of view of the spectroscope is called the spectrum. It is an orderly array of bright coloured lines, each corresponding to a single component in the light analyzed. If a spectroscope is pointed successively to a gas-flame, the sun, the sky, the moon, a salted spirit-flame and a powerful electric spark passing between pieces of metal, the appearances seen are very different in the various cases.

The Frontispiece shows a few typical instances of spectra. We find spectra, in which (as in line 12 of the Frontispiece) the bright lines are sparsely distributed, separated by considerable intervals, each individual line being of uniform colour throughout its length, the different lines being of different colours (as in the spectrum of the electric spark or of some of the nebulæ).

Again we find the bright lines crowded so closely together (see Frontispiece, line 1) that the result is a long continuous band of light—a "*continuous spectrum*" (p.33) —in which the colours are arranged so that the tint passes by a regular and delicate gradation through all the colours of the rainbow (as in the spectrum of a gas-flame or of a white-hot piece of metal or coke).

And yet again we find spectra in which, though the bright lines are in most parts crowded close together, there are dark gaps here and there (see Frontispiece, lines 2, 10); in fact we find what we may call in somewhat Irish fashion a continuous spectrum with dark lines in it (as in the spectrum of the sun and most of the stars).

Across the spectrum—that is, up and down the length of any one line—the colour does not change. Along the spectrum, the order of the colours is always fixed in the field of view of the instrument, that is to say, the red is always to be found at one end; the yellow is always between the red and the green, and so on. The relative intensities or brightness of the different lines or colours may be extremely varied for different sources; for instance, there is plenty of red light visible in the spectrum of a candle-flame, or in the sun, but there is scarcely any in that of a salted spirit-flame.

Experience, accumulated in the study of various terrestrial sources of light and of the conditions under which that light is emitted, enables us to judge of the nature of wholly inaccessible sources, such as the sun and the stars.

CHAPTER I

THE NATURE OF LIGHT—WAVES, RAYS, WAVEFRONTS

1. WHEN sunlight falls on a landscape we see that it affects the various objects, on which it falls, quite differently. If nothing obstructs its path, it illuminates everything; but if a tree or a building stands exposed to it, the light is thereby intercepted from the objects behind, which would be left in complete darkness but for the diffuse light reflected from clouds, sky and surrounding objects, though originally emanating from the sun.

Light is able to pass through some substances, such as air, glass, water. It is reflected from polished surfaces. It is diffused by rough surfaces. Most substances absorb some of the light that falls upon them; black substances absorb all, or nearly all the light that falls on them; coloured objects absorb only a part, and diffuse or reflect or transmit the rest. Unless a body is itself luminous, like a flame giving out light of its own, it is only visible so long as light falls upon it so that it is supplied with light which it can diffuse.

We are so familiar with daylight, that we are apt to regard it as something that is "there" all day long, instead of something that is continually arriving, constantly being used up, and as constantly being replaced by fresh arrivals.

What this unrecognized gift is, one only realizes when one reads of huge engines of 5000 horse-power

working to maintain the comparatively feeble illumination that can be obtained at night in the small area of a town.

2. Light travels from point to point, not instantaneously, but with a very great velocity. If we are told that it takes years for the light to pass from the nearest star to the earth, we are apt to be more impressed with the idea which it conveys of the distance of the star than with the enormous velocity of light.

In the years that intervene between the departure of the light from a star and its arrival at the earth, the light must have been somewhere. All the evidence points in one direction, and we are convinced that the light has been travelling across space through a medium which pervades the whole of the universe. [By the word *medium* must be understood matter of some kind, however attenuated, occupying the space in which the action considered takes place.] This medium we call the light-carrying or luminiferous ether, or briefly the ether.

The velocity of light is 186,000 miles per second, or close upon 300,000 kilometers per second. This is the velocity of light in space which is commonly described as empty, but is in reality filled with ether; and at present the evidence indicates that in space there is no difference of velocity depending on the colour of the light; from the stars red light, for instance, travels as fast as blue, until it reaches the earth's atmosphere. Through air light travels slightly more slowly, its velocity being reduced from 186,000 to about 185,940 miles per second; the reduction is slightly greater for violet than for red light. In water light travels with only about three-quarters of the velocity in free ether, and in glass of different kinds the velocity is reduced to two-thirds or even one-half its value in free ether. Some heavy crystals have been found in which the velocity of light is reduced to about 62,000 miles a second.

TABLE I. VELOCITY OF LIGHT.

	Kilometers per second.	Miles per second.
In free space or "in vacuo"	299,460	186,000
In air	299,370	185,940
In water, violet light	223,500	139,000
In water, red "	225,000	140,000
In crown glass, violet light	194,000	120,500
In crown glass, red "	197,000	122,360
In crystals of chromate of lead, violet	101,000	62,730
In crystals of chromate of lead, red	119,000	73,920

It should be noted that in several cases different velocities are recorded for violet and red light. The power of the spectroscope to analyze light depends on our making use of phenomena which arise from this difference of velocity of the various coloured lights in passing through transparent substances such as glass or liquid (see page 26).

Ether is to be regarded as permeating all material substances, and when light is said to pass through glass, it really passes through the ether in the interstices between the particles of glass, its velocity being reduced because the properties of the ether are changed by the fact that the particles of glass are embedded in it. Each kind of matter affects the ether within its pores in its own peculiar fashion, and hence we get the varied effects that are observed in the phenomena of light.

3. The study of light has led us to believe that it is not produced by the emission of particles which travel from the source to the things which it illuminates. We *see* a star because some subtle disturbance is set up by processes going on in the star analogous to those going on in any flame; these disturbances originated by the particles in the flame or the star are communicated to the ether as tremors, which pass from point to point in the ether with the velocity of 186,000 miles a second, and after the lapse of a time, which depends on the

distance of the star or the flame, reach the eye of the observer and give rise to the sensation of light.

A stone thrown into a still pond sets up a disturbance at the surface in the roughest possible manner by plunging through the surface of the water, pushing it on one side and leaving it to return to its state of rest as best it may; and there arises an exquisitely symmetrical and regular set of concentric ripples. The ripples travel onwards in expanding circles, till they meet with obstacles which either absorb or reflect them. In the case of light, the minute disturbances set up by the incandescent particles in the flame or the star give rise to tremors or waves of excessively minute size, propagated with very great speed in all directions through the ether.

It will presently be clear that we are able to gain knowledge through the channel of spectrum analysis by drawing inferences from phenomena which we control when dealing with light on its way from the source to the eye. For we are dealing with waves and not with either the disturbances at the star or the disturbance in the eye or the brain. Whatever these disturbances may be, it is certain that in the intervening medium minute tremors or waves of some sort are, as it were, the messengers by which the observer is made aware of the existence of the star. We call the waves, waves of light.

We shall have to use the terms wavelength of light, frequency of vibration or, more briefly, frequency, period of vibration, amplitude of vibration. We can arrive at a clear understanding of these terms by considering a special case of wavemotion in which the waves are visible, the case of ocean waves. Let us suppose that we are stationed at such a distance from the waves that we can see a number of them at the same time, and can distinguish the crests and troughs or depressions as they pass.

Wavelength.—The distance between two successive crests, or between two successive troughs, or between

any two corresponding points on successive waves is called the wavelength, the distance being measured along the direction in which the waves travel.

Frequency.—If we count how many crests, or how many troughs pass a fixed point in a given time, we can arrive at a number giving the frequency of the waves, that is, the number of waves that pass the point per second. Let us confine attention to a post fixed upright in the water so that the waves travel past it; we notice that certain parts of the post are alternately exposed and hidden. The surface of the water at the post rises and falls rhythmically; it is at its highest point when the crest of a wave passes and at its lowest when the trough passes. The surface vibrates up and down the post *P* between the points *C* and *T* (Fig. 1). In the time that the surface takes to complete one whole vibration up and down the post, one whole wave passes the post.

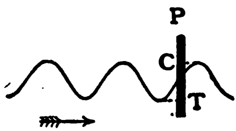


FIG. 1.

Hence, whether we count the number of waves that pass the post in one second, or the number of times that the surface vibrates up and down the post in one second, we arrive at the same number as representing the frequency.

Between *Waves and Vibrations* there is always intimate connection. If, in the space where waves are passing, we confine attention to a region which is small compared with the wavelength—as, for instance, to the immediate neighbourhood of the post just referred to—we become aware that the particles are vibrating up and down, or round and round, over the same paths repeatedly. It is only when we come to consider how the vibrations of neighbouring particles are co-ordinated through more extended regions, that we realize that the onward travel of the wave is the external sign that a disturbance is propagated with a definite velocity from particle to

particle, and hence through the space where the particles abide. A train of waves following one another is a sign that there is vibratory disturbance in each region of the space through which they pass.

The Period of Vibration is the time which is required for the complete performance of one oscillation or vibration.

The Amplitude of Vibration of the surface of water up and down the post is the length of the extreme excursion of the vibrating surface, namely the distance *C T* in Fig. 1. The term amplitude refers strictly to the vibrations of particles, but it is convenient also to use the term in connection with waves. Waves having the same wavelength may have entirely different amplitudes (Fig. 2).

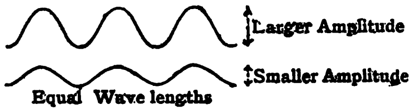


FIG. 2.

We can find a simple relation between the velocity of propagation of waves and the wavelength and period or frequency in the following way. The velocity V of propagation is expressed by saying that the wave travels so many feet a second. The crest of a wave travels over a distance equal to the length of a wave in the period of vibration of the surface of water up and down the post. If the wavelength is 40 feet, and the period of vibration is 2 seconds, the velocity is $\frac{40}{2}$ or 20 feet per second. If the wavelength is λ feet, and the period of vibration is τ seconds, the velocity is $V = \frac{\lambda}{\tau}$ feet per second.

We may arrive at an expression for the velocity in another way. If n waves per second pass a certain point, the crest of the first wave will have travelled

to a distance n times λ in one second, and the velocity is therefore

$$V = n\lambda \text{ feet per second.}$$

Atlantic rollers have been observed which were 500 feet from crest to crest, and took 10 seconds to pass a fixed point. Their velocity would therefore be 50 feet a second; for n is $\frac{1}{10}$th of a wave per second.

Colour and Wavelength.—Now in the case of light we attribute

Difference in brightness to difference in amplitude:

Difference in colour to difference in vibration-frequency.

Since *in vacuo* all light travels with the same speed whatever be its colour, we see that to every vibration-frequency corresponds a definite wavelength *in vacuo*, and we agree to specify colour in terms of wavelength, always bearing in mind that *the wavelength there referred to is that measured in vacuo.* The need for the italicized stipulation arises from the fact that the actual wavelength in any medium depends on the velocity in that medium; thus it happens that while *in vacuo* the wavelength of red light is greater than that of green, the wavelength of red light in glass is less than that of green *in vacuo*, though it is greater than that of green in glass. Colour depends fundamentally on the frequency of the waves that arrive in the eye, but we utilize measurable wavelengths as an indirect means of getting at the unmeasurable frequency.

To take a definite instance, in ordinary circumstances green light is a mixture of various coloured lights; there are many mixtures that would give rise to the sensation of green. But in physical experiments it is possible to produce a green light which is pure, in the sense of its not being a mixture, and we speak of this green light as being of a particular wavelength. We call such light "*homogeneous*"—all of the same kind—when it is completely of one definite

wavelength and not a mixture of lights of different wavelengths. We have reason to know that if we arrange the colours, each being regarded as homogeneous, in the following order—violet, indigo, blue, green, yellow, orange, red—then the wavelengths corresponding to these separate colours are arranged in order of magnitude, the wavelength of violet being least, and that of red being greatest. Further, the frequency of vibration corresponding to these colours will be arranged in order of decreasing magnitude.

TABLE II. COLOURS, WAVELENGTHS AND FREQUENCIES

	Wavelengths.	Frequencies.
Violet	4200 tenthmetres	713 billion per second
Indigo	4500 ,,	666 ,, ,,
Blue	4700 ,,	638 ,, ,,
Green	5000 ,,	600 ,, ,,
Yellow	5700 ,,	520 ,, ,,
Orange	6000 ,,	500 ,, ,,
Red	6500 ,,	462 ,, ,,

The unit, "tenthmetre," is explained in the next paragraph but one.

In physical experiments we have knowledge of lights of all intermediate wavelengths, and consequently the change from one colour to another may be regarded as bridged over by an infinite number of steps.

Wavelengths of light are expressed in terms of "tenthmetres" (also called "Angström units"); these units are so small that ten of them amount to only one-millionth of a millimetre. The origin of the unit is curious. A tenthmetre is the unit of length got by subdividing a metre into a number of parts represented by 1 followed by ten noughts, 10,000,000,000, or, as it is often written, 10^{10}, which means ten multiplied by itself ten times, or ten raised to the tenth power.

$$1 \text{ tenthmetre} = \frac{1}{10^{10}} \text{ metre} = \frac{1}{10,000,000,000} \text{ metre.}$$

The metre is $39\frac{37}{100}$ inches; the millimetre, which

is one-thousandth of a metre, is $\frac{10}{254}$ths of an inch; hence a tenthmetre, which is one-tenth of a millionth of a millimetre, is $\frac{1}{254,000,000}$th of an inch.

The wavelength of green light is about 5000 tenthmetres, or $\frac{1}{50,000}$th of an inch.

In Table II above, the wavelengths are taken in round numbers from the results of actual measurement of a very refined character (see Chap. XIV). The frequencies are deduced from the relation which has been expounded on page 15, viz. $V = n\lambda$. In it we know that V, the velocity of light, is 299,460 kilometres per second. Taking the case of violet light, of wavelength 4200 tenthmetres, we find the frequency by finding the number by which 4200 tenthmetres must be multiplied to give 299,460 kilometres, or 299,460,000 metres, or 2,994,600,000,000,000,000 tenth-metres. The number required is 713 billion, and represents the number of vibrations per second.

Waves and Rays. Wavefronts.

When light passes through any single medium, such as air, then if that medium is homogeneous (*i.e.* of the same nature throughout, not hot or compressed in some parts, and cold or rarefied in others), the path along which it travels from point to point is straight. If, for instance, we look at a candle-flame through a small hole in a screen (Fig. 3), we can only see it when the eye, the hole and the flame are in one straight line. This gives us the idea of rays of light; we imagine each point in the candle-flame emitting rays of light in all directions, and the action of the perforated screen is to cut off all rays that fall upon it except those which pass through the hole.

We shall frequently use the conception of rays, but it must be remembered that a juster view of the matter is to think of each point of the candle-

flame emitting waves which follow one another in stupendously rapid succession.

The ray indicates the direction along which the waves travel, and is, so far as the phenomena to be

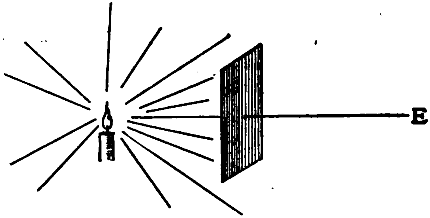


FIG. 3.

dealt with in this primer are concerned, to be considered as being always at right angles to the fronts of the waves. When waves spreading from every point in a candle-flame (Fig. 4) reach a screen in

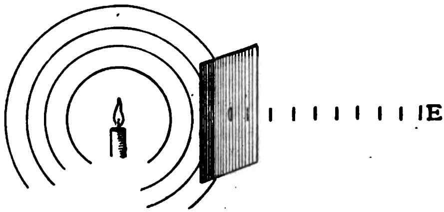


FIG. 4.

which there is a small hole, only small parts of the successive waves pass through the hole, following one another along the direction of the ray.

Wavefronts.—Fig. 5 represents in perspective a few waves travelling along the surface of water in the direction of the arrow. If we were looking at the waves advancing, we should have no hesitation in describing the fronts of the waves as being parallel to such lines *A A*, *B B*, etc. Most spectators would

think of the lines drawn along the *crests* as fronts, and would see the advance of the waves by confining attention to them; but clearly the lines drawn along the troughs, as at *D D* (or through any set of corresponding points either on the rising or on the falling side of a wave, as at *E E*), also advance, and the feature of the advance is that these lines travel parallel to one another, and at right angles to the direction of propagation. In the figure, the inclination of the lines *A A*, *B B*, etc., to the direction of the arrow is a result of perspective. But if we could watch the waves from a point vertically above them, we should see that the waves travel in such a manner

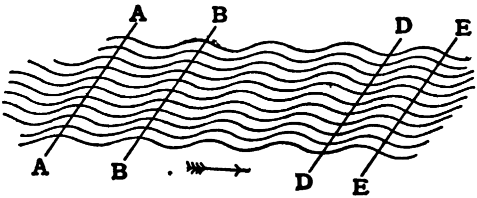


FIG. 5.

that the fronts are always at right angles to the direction in which they travel. We see that each line *A A*, *D D*, *E E* has been drawn through a set of contiguous points at which the phase of the wave-motion is similar, *A A* through points on one and the same crest, *D D* along one and the same trough, and so on. In this sense any of the lines indicates the wavefront. So, when a stone is thrown into still water and the waves spread on the face of the water, the lines representing the wavefronts are not straight but circles. But if we consider the case of sound or of light, we shall realize that we have to apply to the expression "wavefront," a meaning slightly more difficult to grasp. Sound or light emitted from any point or origin in an open space at any instant is propagated with a certain velocity in all directions,

upwards and downwards as well as laterally; at any instant it reaches simultaneously points which lie on a spherical surface or globe surrounding the origin (Fig. 6). This surface defines the limits which the disturbance has reached at the instant considered, and is called the wavefront. Thus the wavefront at P is the small part of this surface as it passes across P. If the wavefront of disturbances emanating from O is required at Q, we have only to consider the expanding surface when it reaches Q; the wavefront at Q coincides with the part of that surface that passes across Q.

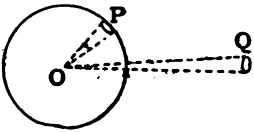


FIG. 6.

In general we have to deal with but very small parts of the whole wavefront. Thus, to take the case of a small beam of light passing through a small square hole in an opaque screen, Fig. 7 represents

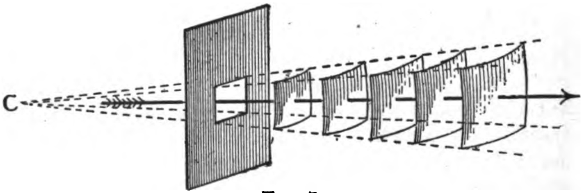


FIG. 7.

in perspective a number of successive wavefronts, or equally well a single wavefront in a number of successive positions; the dotted lines represent the rays that correspond with the corners of the beam emanating from the source C.

Fig. 4 on page 18 may now be referred to once more, and the fuller meaning of the simple representations there adopted will be realized.

Each of the wavefronts represented in Fig. 7 is a curved surface. In the following pages we shall often have to deal with flat or plane wave-

fronts. Curved wavefronts are connected with rays that are either divergent or convergent. Plane wavefronts are connected with beams of parallel rays. Fig. 8 represents a series of plane wavefronts in perspective.

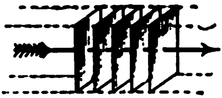


FIG. 8.

REFLECTION, REFRACTION, DISPERSION.

In any one medium, light travels in straight lines, but it may be bent out of its course by three different processes—reflection, refraction and diffraction.

Reflection.—When a beam (that is, a bundle of rays) of light falls on a mirror, the beam is bent or reflected, and the perpendicular or normal *P N* to the mirror at the point of incidence *N* always bisects the angle between the incident and reflected rays. The rays are straight as they approach the mirror, and again straight as they recede from it; they are broken and reflected at the mirror (Fig. 9). An eye placed at *E* sees the light as if it emanated from a point somewhere on the ray *E I*.

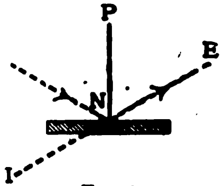


FIG. 9.

Refraction.—When a beam of light passing through one transparent medium, *e. g.* air, falls on the surface of another, *e.g.* water, the beam is broken or refracted, as it passes into the second medium. The ray is straight till it meets the water, and is again straight when passing through the water; the refraction takes place at the surface where air and water meet. When the ray *A N* (Fig. 10) meets the surface at *N* it is refracted in the direction *N R* and deviated out of its original course, the deviation being measured by the angle *D N R* between the original course *A N D* and the new course *N R*. In one case only is there no deviation, that is when the beam falls

perpendicularly on the surface; in this case the beam passes straight on, as at *P F*. Deviation increases as the angle of incidence increases.

The deviation of the ray in the case of refraction is a result of the difference in the velocity of light in the media on the two sides of the surface at which refraction takes place. Experiment proves that light travels more slowly in water than in air (see page 10). Let us now proceed to consider how this experimental fact, combined with the conception of advancing wavefronts, gives what may seem an easy explanation of the deviation. Consider wavefronts advancing in the direction indicated in Fig. 11 by the arrow. They

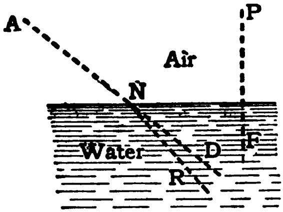


FIG. 10.

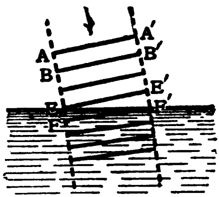


FIG. 11.

follow one another at regular minute intervals, so minute, in fact, that in the figure we must imagine that there are 5000 waves between the successive lines *A A′*, *B B′*, which are one-tenth of an inch apart.

If we follow the movement of one particular wavefront, we may represent it as reaching the positions *A A′*, *B B′*, *C C′*, etc., after successive equal intervals of time. When the front reaches the position *E E′* the wave at the end *E* is ready to enter into the water, whilst at the other end, at *E′*, it still has some air to travel through before reaching the water, and by the time that *E′* has reached *F′*, the wave has travelled through a shorter space in the water, because it travels in it more slowly. Hence the wavefront now represented by *F F′* is travelling in a slightly different direction in the water.

If we attempt to represent the wavefront in positions intermediate between *E* and *F*, Fig. 12 gives a fair representation.

The index of refraction of a substance (often indicated by the letter μ) is a number which expresses the relation between the velocity of light in free space, and the velocity of light in the medium. Thus for the case of water, light travels 1·33 times as fast

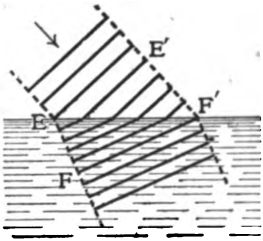


FIG. 12.

TABLE III. REFRACTIVE INDICES.
(For yellow light.)

	μ Refractive index.
Air	1·00029
Water	1·333
Crown glass	1·517
Flint glass (light)	1·574
,, ,, (dense)	1·622
,, ,, (extra dense)	1·650

in free space as in water; the refractive index of water is 1·33. Light travels very nearly at the same rate in air as in free space, and for our present purposes we may regard the velocity in air and free space as equal, and the refractive index of air as 1·00.

Let us now consider more closely the turning of the wavefronts as they pass from air to water. The front *A B* (Fig. 13) is turned into the position *C D*; the end *B* travels to *D* through air in the same time as the end *A* travels to *C* through water; the length *B D* is therefore 1·33 times the length *A C*. Observe that the ray

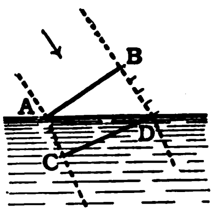


FIG. 13.

BD is perpendicular to the wavefront AB, and that the ray AC is perpendicular to the wavefront CD. Here then we have an indication of the method of drawing correct diagrams for the refraction of rays:—From D on the ray DB mark off a length DB proportional to the refractive index. From B draw BA perpendicular to BD, to meet the surface DA in A. Bisect AD at O, and with centre O describe a circle with radius OD or OA. Then, with centre A and radius equal to unity on the same scale as was used in measuring DB, describe a circle, cutting the first circle DBA in C. Then AC gives the direction of the refracted ray. Draw AF parallel to DB, and draw DE parallel to AC, join CD. Then AB and CD are wavefronts; BD and FA are incident rays, and AC and DE are refracted rays.

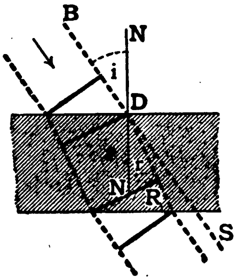


FIG. 14.

A ray is said to fall normally, or with normal incidence on a surface when it falls perpendicularly on the surface. In Fig. 14 the ray BD falls on the surface at D with incidence i, where i is the angle NDB between the normal ND and the ray BD, and i is called the angle of incidence of the ray BD.

If the normal ND is produced to N', the angle $N'DR$ is the angle which the refracted ray makes with the normal $N'D$; it is often called the angle of refraction, and denoted by r.

If the ray BD had passed on through D without being refracted, it would have passed along DS. By refraction the actual ray DR has been deviated through the angle RDS. This angle is generally called the deviation of the ray, and is equal to $i-r$.

Fig. 14 indicates how rays traversing a plate of glass, of refractive index 1·5 and with parallel faces, pass

with lateral displacement, the angular deviation at the second surface completely counteracting that at the first; Fig. 15 indicates how rays traverse a block of glass, of refractive index 1·66 and with inclined faces, and suffer permanent deviation, the deviation at the second surface conspiring with that at the first surface to produce a total angular deviation, which is indicated by the inclination of the direction of the emergent ray to the original incident ray.

Fig. 15 represents the case of refraction through a prism in a particular case, namely, that in which the refracting surfaces of the prism are perpendicular to the plane of the paper (that is, when the paper is in the principal plane of the prism).

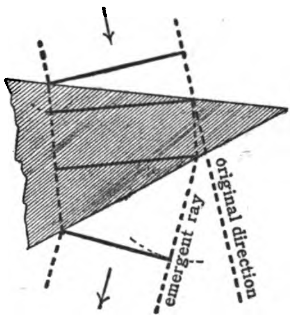


FIG. 15.

If the reader will draw out the figures again for the cases where the slab of glass has a refractive index of 1·66, and the prism has a refractive index of 1·5, he will be able to convince himself that for the slab or plate with parallel faces the emergent ray is still parallel to the original direction, and that this parallelism is true for all plates with parallel faces whatever their material and refractive index may be, and also whatever the angle of incidence may be. For the prism on the other hand he will find that the deviation depends not only on the original incidence of the rays on the first surface but also on the refractive index of the prism, and, further, that when the circumstances are such as to make the comparison fair, the deviation is greatest for that prism which has the greater refractive index.

The reader will now realize that if the glass of

which the prism is made transmits red light with greater velocity than blue, and if both red and blue light fall simultaneously with the same incidence on the first surface of the prism, then the blue light will be deviated more than the red by its passage through this prism. Such difference in deviation or refraction constitutes what is known as dispersion, or the separation of coloured beams from one another by virtue of their different refrangibility.

Thus whereas in the incident beam red and blue lights may travel along identical paths, still after passing through the prism they emerge with new directions, all the blue rays going in one direction, and all the red rays going in a slightly different direction. Hence, were a screen set up at a considerable distance from the prism, the blue rays would illuminate one part and the red rays another part. If the screen were gradually moved towards the prism, the blue and the red patches on it would gradually approach one another, until they completely overlap when the screen is quite close to the prism; this alone would show that the beams diverge from the prism. (See Fig. 18.) The angular separation, which the prism produces in the differently coloured lights, constitutes *dispersion*, on which the power of the spectroscope to analyze light depends.

Table IV. gives the refractive indices of three different kinds of glass for light of different colours.

TABLE IV. REFRACTIVE INDICES.

Colour.	Wavelength.	Crown glass.	Light flint glass.	Dense flint glass.
Red	6562	1·5145	1·5700	1·6175
Yellow . . .	5890	1·5171	1·5740	1·6224
Green. . . .	5166	1·5210	1·5803	1·6302
Blue	4340	1·5280	1·5922	1·6453
Violet . . .	3968	1·5328	1·6007	1·6562

CHAPTER II

NEWTON'S DISCOVERY, 1675

The composite nature of white light.

IN the year 1675, Sir Isaac Newton (1642–1727) presented his memoir on Optics to the Royal Society. This is the treatise in which Newton proved that white light is a mixture of coloured lights, and showed how the component coloured lights could be separated from one another.

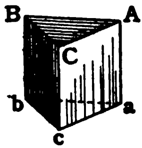


FIG. 16.

In his experiments, a beam of sunlight was allowed to fall upon a prism of glass. The figure represents a prism such as is used for spectroscopic purposes. It is a solid piece of glass bounded by five plane surfaces; two surfaces are triangles ABC and abc; they are parallel to one another and are now generally known as the top and bottom of the prism, inasmuch as usually the prism in the spectroscope is made to stand on one of these triangular ends. The other three surfaces are rectangles $ACca$, $ABba$ and $BCcb$; of these the two first named are carefully ground flat and polished; they meet along the edge Aa, which is called the refracting edge of the prism. The third rectangular face $BCcb$ is generally ground flat and left unpolished, and it is usually called the base. The angle CAB between the polished faces is known as the refracting angle of the prism, and is very commonly an angle of about 60°.

Newton in his experiments set the prism in a position in which the refracting edge was horizontal, and the base $BCcb$ uppermost. The following is the description which he gives of his classical experiment: [3rd Edit. *Opticks*, p. 21.]

"Prop. II. Theor. 2.—The light of the sun consists of rays differently refrangible.

"THE PROOF BY EXPERIMENTS.

"Exper. 3. In a very dark chamber at a round hole about one-third part of an inch broad made in the shut of a window I placed a glass prism, whereby the beam of the sun's light which came in at that hole might be refracted upwards toward the opposite wall of the chamber, and there form a colour'd Image of the Sun. The axis of the prism (that is the line passing through the middle of the prism from one end of it to the other end parallel to the edge of the refracting angle) was in this and the following experiments perpendicular to the incident rays. About this axis I turned the prism slowly, and saw the refracted light on the wall or coloured image of the sun first to descend, and then to ascend. Between the descent and ascent when the image seemed stationary, I stopped the prism and fix'd it in that posture, that it should be moved no more. For in that posture the refractions of the light at the two sides of the refracting angle, that is at the entrance of the rays into the prism, and at their going out of it were equal to one another. So also in other experiments, as often as I would have the refractions on both sides of the prism to be equal to one another, I noted the place where the image of the sun formed by the refracted light stood still between its two contrary motions, in the common period of its progress and regress; and when the image fell upon that place, I made fast the prism. And in this posture, as the most convenient, it is to be understood that all the prisms are placed in the following experiments, unless where some other posture is described. The prism therefore being placed in this posture, I let the refracted light fall perpendicularly upon a sheet of white paper at the opposite wall of the chamber, and observed the figure and dimensions

of the solar image formed on the paper by the light. This image was oblong and not oval, but terminated with two rectilinear and parallel sides, and two semicircular ends. On its sides it was bounded pretty distinctly, but on its ends very confusedly and indistinctly, the light there decaying and vanishing by degrees. The breadth of this image answered to the sun's diameter, and was about two inches and the eighth part of an inch, including the penumbra.

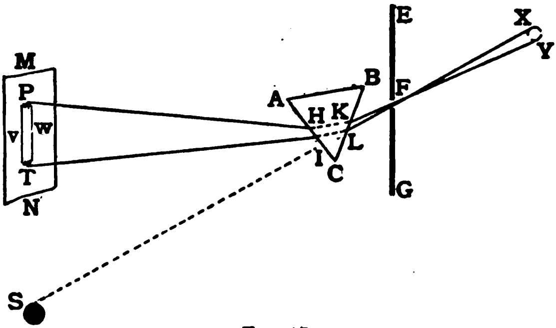


FIG. 17.

For the image was eighteen feet and a half distant from the prism, and at this distance that breadth if diminished by the diameter of the hole in the window shut, that is by a quarter of an inch, subtended an angle at the prism of about half a degree, which is the Sun's apparent diameter. But the length of the image was about ten inches and a quarter, and the length of the rectilinear sides about eight inches; and the refracting angle of the prism whereby so great a length was made, was 64 degrees. . . .

"And therefore seeing by experience it is found that the image is not round but about five times longer than broad, the rays which going to the upper end *P* of the image suffer the greatest refraction, must be more refrangible than those which go to the lower end *T*, unless the irregularity of refraction be

casual. This image or spectrum was coloured, being red at its least refracted end *T*, and violet at its most refracted end *P*, and yellow, green and blue in the intermediate spaces. Which agrees with the first Proposition, that lights which differ in colour do also differ in refrangibility."

By this and other experiments Newton showed that white light consists of a mixture of coloured lights differently refrangible. The difference of refrangibility arises because differently coloured lights travel through the glass with different velocities. Violet waves travel more slowly through glass than red, and they are more deviated at entrance into the prism and emergence from it. Herein is the foundation of spectroscopy. The word spectrum is used for the first time, in this connection, in the paragraph just quoted from Newton. The reader is urged to repeat Newton's experiment.

Newton went on to show (i) that if the coloured lights were mixed together again, the resultant compound was white, (ii) that each of the component colours was simple, *e.g.* that the red part of the image if separated from the rest of the spectrum could not be resolved into further components by a second prism. The composite nature of white light was thus demonstrated.

Fig. 17 is a copy of Newton's figure with one addition, namely the dotted line showing the position of the direct (unrefracted) image of the sun on the screen at *S*. The ray *FK* is bent at *K*, and further bent at *H*, so that instead of going direct to *S* it is bent or refracted to *P*. Newton turned the prism, without altering its distance from the screen, till *T* was as near to *S* as possible; that is, till the deviation was as small as possible—a minimum. In this position or posture, the prism is said to be set for minimum deviation. The reader is urged to repeat Newton's experiment, with special reference to observing the position of the prism.

We shall see, in Chap. VI., the importance of making use of broad beams of light in spectroscopy. Hence, it will be well to consider how a broad beam of parallel rays (or briefly, a broad "parallel beam") passes through a prism (Fig. 18), and we will for simplicity first consider a beam of pure red light, *i.e.* red light that is not a mixture of colours but is of one definite refrangibility. The limiting rays in the beam are *A B*, *O P*; the beam falls on the prism which we will suppose to be set for minimum deviation. Part of the incident light is reflected and a beam of parallel rays passes off in the direction *B X*, *P Y*. The rest of the light passes into the prism, but its course is deviated, each ray being deflected by the same amount; the rays *P Q* and *B C* are therefore parallel to one another. At *Q* and *C* each ray again suffers refraction and is deviated by the same amount, and the emerging rays *Q R* and *C D* are consequently still parallel.

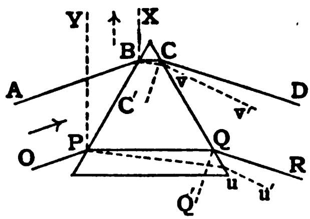


FIG. 18.

And again at *Q* and *C*, part of the incident light is also reflected in the directions *Q Q′* and *C C′*. The paths of the limiting rays being thus indicated, it is easy to picture the directions of intermediate parallel rays. Hence a parallel beam of red light incident on the prism is still a parallel beam on emerging from the prism. If the original incident beam had been a beam of violet light instead of red, the deviation would have been greater, so that the violet ray at *P* passed along the line *P U* instead of *P Q*; and similarly the violet ray would have passed along the line *B V* instead of *B C*. And again at *V* and *U*, the deviation would have been greater, and the violet beam would have emerged and passed along

the courses $U U'$ and $V V'$—a parallel beam of violet light.

If the incident beam consisted only of red light the refracted light would form on the screen a red patch of a size equal to that of the cross section of the beam. If the incident light had consisted only of violet light, the refracted light would have formed on the screen a violet patch in a different position. If the incident beam had been a beam of sunlight, in which all sorts of colours are present, there would have appeared on the screen a band of colours, which may be regarded as a succession of overlapping patches of light of varied colour.

When one colour appreciably overlaps another, we describe the spectrum as impure. In Newton's experiment, the amount of overlapping depends on the size of the image of the sun as compared with the length of the spectrum. This ratio was about 2 inches to 10 inches, so that the overlapping was considerable and the spectrum was consequently impure. But further on in his treatise he described an optical device that enables us to form a pure spectrum in a simple manner. The reader is urged to find some opportunity of performing the experiments now to be indicated.

Method of forming a pure spectrum.

Let light pass through a narrow slit, forming a divergent beam, which would illuminate feebly a large surface of a distant screen placed opposite to it. If now a properly chosen lens be placed in the divergent beam, the divergent rays are so deviated in passing through the lens that they emerge as a convergent beam and can be concentrated upon a screen. In this manner an image of the slit is formed on the screen. The slit, the lens and the image I lie in a straight line. (Fig. 19.)

Suppose now that a prism is placed close to the lens in the position indicated in the figure. The

prism deals with each component of the light according to its refrangibility. If the convergent beam consisted solely of homogeneous red light it would be refracted by the prism into a new direction, and an image of the slit would be formed at *R* in red light on the screen properly placed.

Had the convergent beam been of homogeneous green light, the prism would have refracted it slightly more, and a green image of the slit would have been formed on the screen at *G*. Had the light incident on the slit (and therefore the convergent beam) been a mixture of homogenous red and homogeneous green lights, the prism would have dealt with the colours separately as described above, and

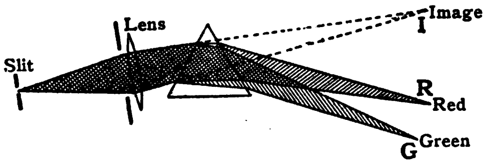


FIG. 19.

there would appear on the screen two images of the slit, red and green, separated by some interval upon the screen. If the beam incident on the slit and lens and prism had consisted of an innumerable number of components, each component would have been dealt with by the prism according to the velocity through the glass, and there would have resulted an innumerable number of images of the slit side by side on the screen, so close to one another as to form a continuous band or strip—a continuous spectrum.

There are, however, objections to allowing a *convergent* beam to fall upon the prism, inasmuch as the definition of the image of the slit is at its best only in the case of that colour, whose convergent beam passes symmetrically through the prism; that is, in such a way that the angle of incidence is equal to the angle of emergence, and the beam in the prism

is parallel to the base. It is therefore customary, when the best results are desired, to use (in place of one lens) *two* lenses arranged in such a way that the beam between them is parallel, *i. e.* consists of parallel rays (see Fig. 20). The lens nearest to the slit is chosen and placed in such a manner that the divergent rays emanating from the slit are rendered parallel in consequence of passing through the lens. The lens is called the collimator (collineator), inasmuch as it brings the divergent rays all into parallelism. The parallel beam emanating from the collimator lens falls upon the prism, and the rays for each separate colour pass in a

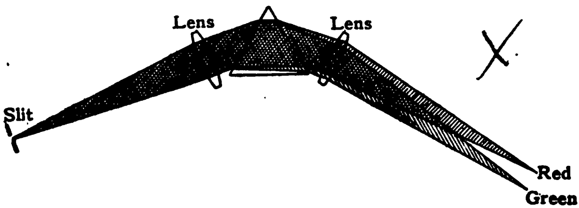


FIG. 20.

parallel beam through the prism and emerge from it still a parallel beam; rays of any other colour, whilst remaining parallel amongst themselves, pass in a slightly different direction and emerge from the prism parallel to one another, but slightly inclined to the rays of the first colour.

Each of the parallel beams falls upon the second lens and is thereby converted into a convergent beam which converges upon a focus and forms there an image of the slit. In this way the images for the different colours are set side by side in the focal plane of the lens where they may be thrown upon a screen or upon a photographic plate, or may be examined by means of an eyepiece.

Fig. 20 shows the arrangement just described. The slit is perpendicular to the plane of the paper,

and is formed by two sharp-edged "jaws" of metal which can be moved further apart or closer together by means of a screw. The refracting edge of the prism is also perpendicular to the paper, and is consequently parallel with the slit. Finally, the images of the slit are perpendicular to the paper, and are parallel to one another and to the slit.

It is to be observed that the angular separation of

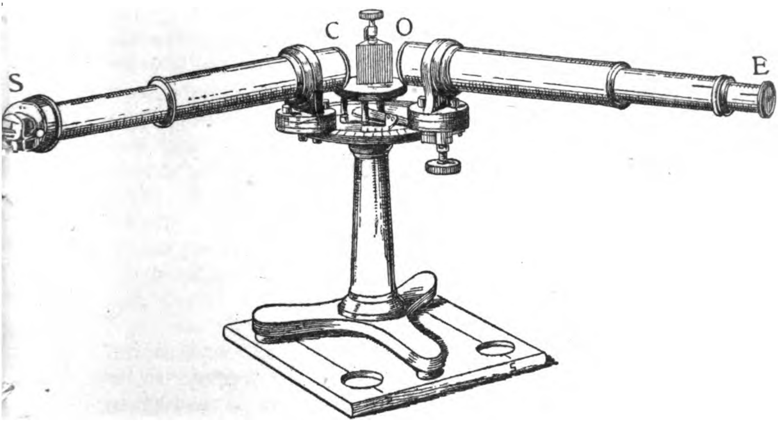


FIG. 21.

the colours is produced by the fact that the prism deviates the beam of parallel green rays more than the beam of parallel red rays. The object-glass receives these two beams, and forms the corresponding red and green images of the slit in its focal plane, in such positions that the two lines drawn from the centre of the object-glass to the images are inclined to one another at an angle exactly equal to the angular separation which the prism impresses on the red and the green beams. It is clear that the greater the distance of the focal plane from the object-glass

(*i. e.* the longer the telescope), the greater is the linear separation (measured in inches in the focal plane) of the red and green images of the slit (see page 70).

Fig. 21 represents a form of spectroscope very commonly used. The slit *S* is fixed in a vertical position at the end of a tube which carries at its other end the collimating lens *C*. The tube or collimator is attached to a firm stage which forms a horizontal table on which one or more prisms can be placed, and means are generally provided for facilitating the adjustment of the prism into its proper position. A second tube *OE*, with a lens or object-glass *O* is provided and fixed to the stage in such a way as to let the beam of light coming from the prism pass along its axis, and at the further end *E* an eyepiece is fixed so as to allow an observer to view the images formed by the object-glass. This second tube is known as the viewing tube or telescope; or if in place of the eyepiece a photographic plate is placed at the end *E*, so that the images of the slit fall upon it, the tube would be called the camera.

The reader is now in possession of the explanation of the principles and action of the spectroscope in its simple form. It would be well for him to read again the paragraphs on pages 7 and 8.

CHAPTER III

MODE OF ADJUSTING AND USING A SPECTROSCOPE

THE spectroscope as supplied by an optician often has certain adjustments made once and for all. These *fixed* adjustments are as follows—

(1) The prism is set so that its refracting edge is perpendicular to the table on which it stands. It

should be possible to turn the prism round on a vertical axis, without upsetting the perpendicularity of its edge to the table.

(2) The collimator tube is set so that its axis is perpendicular to the refracting edge of the prism and passes through the centre of the first face of the prism, in order that as much as possible of the beam that comes from the collimating lens may fall upon the prism and pass through it.

(3) The slit is fixed so that it is parallel to the refracting edge of the prism. If the slit were inclined to the edge of the prism, the lines in the spectrum would appear inclined instead of perpendicular to the length of the spectrum.

(4) The viewing tube or telescope is set so that the beam from the prism passes wholly into and along the tube.

The following adjustments are made by the observer—

(5) *The focussing of the telescope* is accomplished by pointing it at a very distant object, and racking the eyepiece in or out until the object appears distinct. It is usual to arrange cross-wires in the tube of the telescope, which can be seen distinctly through the eyepiece; the eyepiece being movable in a tube so that it can be set to give the most distinct view of the wires. In focussing the telescope, the eyepiece and cross-wires are simultaneously moved, until the distant object and the wires appear equally distinct at the same time.

(6) *The focussing of the collimator* is accomplished by moving the slit relatively to the collimating lens until the rays issuing from the lens are parallel. To achieve this, the telescope focussed as just described is turned so as to point along the collimator and look at the slit through the collimating lens. Since the telescope is focussed so as to give a distinct view of a remote object, and since rays from any point on that object must be, when they reach the telescope,

to all intents and purposes parallel, it follows that if the slit as seen by the telescope through the collimating lens is distinct and in focus, the rays going into the telescope must be parallel, and these parallel rays are coming from the collimating lens. In this case the adjustment of the collimator for focus would be complete. If, however, the slit as seen in the telescope is not distinct, the slit must be moved a little nearer to or a little further away from the collimating lens, until it is distinct; and for this purpose a slipping or focussing tube is generally provided in the collimator.

(7) *The setting of the prism.*—With the collimator focussed as just described, the prism is to be set on its table and turned about a vertical axis until the light from the collimator falls upon the first polished surface with such an angle of incidence that the light emerges from the second polished surface with an angle of emergence about equal to the angle of incidence. The telescope is then pointed so as to catch the emergent light. The spectrum should be visible through the eyepiece, and the telescope may be turned so that some particular colour (as, for instance, the yellow) appears in the middle of the field of view. If the prism be now turned slightly about the vertical axis, the spectrum will in general move to one side or other, and the prism should be turned in that direction which tends to move the spectrum in such a way that the deviation (as measured by the angle between the telescope and the prolongation of the collimator) diminishes. When in the turning of the prism, the yellow reaches a position from which with further turning of the prism it appears to turn back and move in the opposite direction, the prism is said to pass through the position of minimum deviation for the yellow light. If a salted spirit-flame is used as the source of light, the adjustment can be made with the utmost nicety; and in consequence of the ease with which

this flame can be obtained, it is not an uncommon practice to set the prism for minimum deviation for the yellow light emitted by such a flame.

(8) *The adjustment of the slit.*—The slit is usually made so that its width can be adjusted by means of a screw. In first looking at a spectrum, it is sometimes convenient to widen the slit in order to let more light in; the result of this is that if the spectrum examined is a continuous spectrum or the solar spectrum, every part of it is made brighter and one can readily find the special part to be observed, *e. g.* the green, or the red. Then the slit can be made narrower, and the purity of the spectrum is thereby increased enough to let any special features be seen.

When the adjustments of the spectroscope have been completed, the collimator and prism are fixed in their proper positions; but the telescope is mounted in such a way that it can be turned about a vertical axis which passes through the prism, so that within certain limits it can be pointed towards the prism from many points of view. In this manner it can be set so as to receive from the prism the beams of coloured light emanating from it, in whatever direction they may travel from the prism. The position of the telescope can be noted with respect to numbered divisions on a divided (graduated) circle, and if some peculiar feature be observed in a spectrum, its position in the spectrum can be defined by the number on the divided circle which defines the position of the observing telescope, when the peculiar feature falls on the cross-wires in the field of view of the telescope.

FIG. 22.

With reference to the cross-wires, it may be said that for simple work it is found convenient to have two fairly thick fibres, or thin wires, fixed diagonally so as to appear as shown in Fig. 22, where the circle represents the

boundary of the field of view of the eyepiece, and *AB* and *CD* represent the cross-wires; these are inclined to one another at an angle of about 30°, and are used in the following way.

Mapping a Spectrum.

Let us suppose that the spectrum observed is that of an electric spark between metal points. Fig. 22 shows a portion of the spectrum (in negative) with the cross-wires showing up upon it. The bright lines *L M N* in the spectrum are characteristic either of the nature of the metal points between which the spark passes, or of the gas or air surrounding the points. The telescope is moved until the cross-wires bisect the line as shown in the case of the line *M*. The position of the line is then defined by the number on the graduated circle defining the position of the telescope.

In more refined work—as when the spectrum has very numerous lines in it—the graduations on a circle of ordinary dimensions would be too coarse to enable us to represent the positions of the lines. In such a case the telescope may be moved by a micrometer screw, which has, let us say, 50 threads to the inch; one turn of such a screw in a fixed "nut" would make the end of the screw advance by $\frac{1}{50}$th of an inch, and if one end of the screw butts against the side of the telescope the telescope could be moved through that distance. On the other end of the screw a drum-head is fitted, and it is divided by numbered graduations into 100 equal parts. We can thus estimate changes in the position of the telescope corresponding with a hundredth of a revolution, that is, with $\frac{1}{5000}$th of an inch. Hence instead of referring the position of a line in the spectrum to divisions on a coarsely divided circle, we may refer them to the numbers defining the number of revolutions and parts of a revolution of the micrometer screw.

A third method very convenient for a rapid survey may also be described. This consists briefly in throwing into the same field of view as the spectrum, the image of an illuminated scale; for this purpose an ingenious optical device is used. A tube *S* (Fig. 23) very similar in principle to a collimator, fitted rigidly in the proper direction on to the frame of the spectroscope. The tube has a lens at the end near the prism, and at the other end is fixed a minute scale etched on glass, or a minute photographic

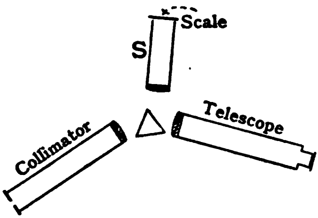


FIG. 23.

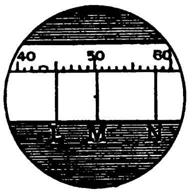


FIG. 24.

transparency. The scale is fixed at the principal focus of the lens, that is, at such a distance from the lens that the rays of light proceeding from each point of the scale pass out of the lens in parallel beams. These fall upon the polished surface of the prism (the second face), and are reflected into the telescope as parallel beams. The observer is thus enabled to see a distinct image of the scale superposed or partly superposed upon the spectrum. Fig. 24 represents the appearance in the eyepiece.

The positions of the lines *L M N* are read off by inspection as follows:

Line.	Scale numbers
L	45·1
M	50·2
N	58·0

The positions of lines in the spectrum are thus noted in terms of readings on an arbitrary scale. To

convert these into wavelengths, a simple plan is to use a graphic method. Readings are noted for certain lines (standards) of recognized wavelength (see Table below), such as red lithium line at reading 39·0, yellow sodium line at 58·3 and so on. The lithium line is then recorded on accurate squared paper by a dot at wavelength 6708 and scale reading 39·0; the sodium line by a dot at wavelength 5890 and scale reading 58·3 and so on; and a smooth curve is drawn through the dots. If with the same adjustment of the spectroscope an unknown line is seen at reading 71·0, we deduce directly from the curve that it has wavelength 5560.

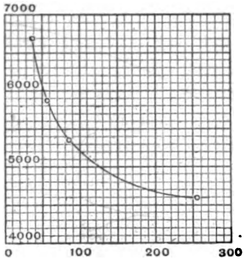


FIG. 25.

TABLE OF WAVELENGTHS FOR STANDARD LINES.

Flame.		Spark.		Sun.	
Strontium	4668	Cadmium	4678	F	4862
Thallium	5351	,,	5086	b_1	5184
Sodium	5890	,,	5379	D_2	5890
,,	5896	Mercury	5791	D_1	5896
Lithium	6708	,,	5770	C	6563
		Cadmium	6439		

For the purpose of judging of the identity of two lines in different spectra, Kirchhoff devised the comparison prism. A small reflecting prism *efd* is placed in front of one part of the slit. Light from a source put directly in front of the slit at *F* cannot pass through the part of the slit covered by the

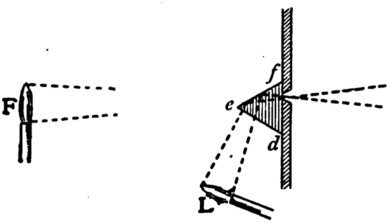


FIG. 26.

reflecting prism, but does pass through the rest, above and below. A second source to be compared with the other is placed at L in the proper position relatively to the reflecting prism, so that its light is reflected by face ef of the prism through just that part of the slit which is protected from the source in front of the slit. Thus two neighbouring parts of the slit receive samples of light from the two sources whose spectra are to be compared, and the observer sees the spectra side by side, and can make out whether any lines are common to the two spectra. (See Plate IB.)

FIG. 27.

For a hasty view of the broad features of a spectrum, a very convenient form of spectroscope is the direct vision spectroscope, of which there are several forms. The commonest is that devised by Amici, in which the prism is compounded of three prisms cemented together, as shown in Fig. 27.

The two outer prisms are made of crown glass, the middle prism is made of dense flint glass with a refracting angle of about 90° or 100°. The crown prisms correct the general deviation of the beam without entirely doing away with the separation of the colours. In the common pocket spectroscope

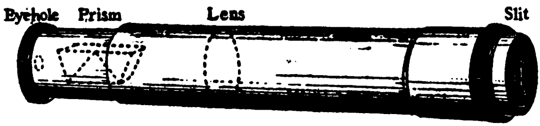


FIG. 28.

illustrated in Fig. 28, a small triple prism of this form is put in a short tube: at one end of the tube is a small circular opening about $\frac{1}{8}$in. in diameter, and at the other end is a lens of focal length about 2in. This tube is pushed, lens first, into one end of another tube that just fits it, and which

carries the slit at its other end. The instrument is arranged so that the lens is about 2 inches away from the slit, and so that the refracting edge of the prism is parallel to the slit, and the final focussing is done by pushing the tube that holds the prism and lens into the tube that holds the slit.

The spectroscopist is frequently troubled in his studies by the faintness of the light, and it is well

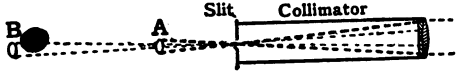


FIG. 29.

here to point out that care should be taken that the source of light examined should be placed in front of the slit of the spectroscope in such a way that the light after passing through the slit spreads out in a diverging beam large enough to fill the collimator lens. In Fig. 29 a collimator is shown with a source of light set in two positions, *A* and *B*, in front of the slit. In position *A*, the light falls on the slit from all parts of the source, and the beam of light inside the

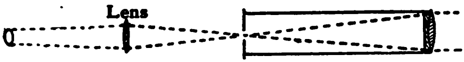


FIG. 30.

collimator is clearly large enough to fill the collimator lens. In position *B*, however, the beam is not large enough to cover more than the central part of the collimator lens. Even in position *A*, if the source of light is very small, the beam may not be sufficiently large. In such a case it is a good plan to use a lens (Fig. 30) to throw an image of the source upon the slit.

Some further advantages arise from this use of an image-lens: they will be referred to more fully in a later chapter. (See page 94 and 158.)

CHAPTER IV

VARIETIES OF SPECTRA

THE function of the spectroscope is to receive a sample of light and to separate the different components, and show them to us arranged side by side in what we call the spectrum. The spectrum is, as it were, a most orderly report, drawn up in the most concise form, of the analysis of the sample of light that passes into the slit of the spectroscope.

In a broad sense then, everything that can be seen has a spectrum; flame, blue sky, flowers, red-hot metal, red glass, sun, electric spark, etc. We can at once divide things into two classes, (1) those that are visible because they emit light of their own, (2) those that can be seen only in virtue of their reflecting, diffusing or transmitting light that falls upon them from other sources.

There is a third class of substances, (viz. fluorescent substances, like fluor-spar, solutions of quinine), of very great interest to those who study the nature of light, and the properties of matter. These bodies, when light falls upon them, absorb a certain part of the light and not only diffuse the residue like bodies of the second-class, but also suffuse from their surface additional light, which persists only so long as the light falls upon them. It is supposed that the energy requisite for the emission of this additional light is derived from that part of the incident light which is absorbed. Another class of these bodies is phosphorescent; these, like luminous paint, etc., when excited by the incidence of light, continue to emit light for some time after they are removed from the influence of the incident light.

In the case of self-luminous sources, the interest is to learn what kinds of light they emit. The

spectra observed when the spectroscope is directed to such sources are called "emission-spectra."

On the other hand experience, which has been gathered chiefly with the help of the spectroscope, shows that bodies that do not emit light of their own, owe their special appearance and colour to the fact that each robs the incident light of some of its components and passes on only a residue, having *absorbed* the rest. It becomes of interest, therefore, to learn what kinds of light a body absorbs. The spectra observed arecalled "absorption spectra."

In an emission spectrum we pay attention to the bright parts, as giving information of the nature of the light emitted. In an absorption spectrum the important characteristic is the dark lines or bands which tell us what part of the light incident on a substance has been absorbed.

Emission-Spectra.

Continuous Spectrum.—When the spectroscope is directed towards the bright part of a candle-flame or of a gas-flame, the spectrum is seen to consist of a bright band of colours, ranged side by side, without any gaps of increased or diminished brightness (see Frontispiece, line 1). The spectrum is in fact continuous. The images of the slit in the different colours are set so close to one another: the colours are so numerous, shading into one another by innumerable gradations: and the successive images are so nearly alike in brightness, that it is not possible to see that any parts of the spectrum are obviously brighter or less bright than the neighbouring parts. The source whose spectrum is found to be continuous must therefore be regarded as emitting light of all kinds with no preferences for special wavelengths.

Extent of the Spectrum.—The continuous spectrum is found, however, to die away into invisibility both at the red and at the violet end. The eye is most

sensitive for the green, and its sensitiveness diminishes as we pass in either direction along the spectrum. The eye is insensitive beyond certain limits at the red end as well as at the violet end, which are slightly different for different individuals. The range of the *visible* spectrum is from about 4000 tenthmetres to about 7500. Special physical methods have however given us knowledge of invisible "light" with wavelengths as small as 1200 tenthmetres, in what is called the "ultra violet," and as large as 150,000 tenthmetres in the "ultra red."

Stokes showed that when a screen, treated with some fluorescent substance such as solution of quinine sulphate is held in the ultra violet part of the spectrum, radiations can be detected which are otherwise quite invisible.

Becquerel found that phosphorescent substances could be rendered luminous by the incidence of ultra red radiation, and he utilized this peculiarity for investigating the ultra red part of the spectrum.

When photographic methods were introduced for recording spectra, we learnt of the existence of ultra violet radiations far beyond the range of sensitiveness of the eye. Schumann has found that when his instruments are enclosed in a vessel from which all the air has been exhausted, he can study by photographic methods light of the shortest known wavelength. Abney has shown how to prepare photographic films sensitive to the ultra red part of the spectrum, and has thus extended our knowledge of that part. Langley, making use of the change which the incidence of light brings about in the electrical properties of certain substances, has detected radiation in the ultra red far beyond the reach of even Abney's special photographic plates (page 122).

When the cases in which a continuous spectrum is observed, are compared one with another, we are led to the conclusion that all incandescent solid and liquid bodies (*e. g.* white hot copper, or molten iron) give

a continuous spectrum, the extent of the spectrum depending on the temperature of the incandescent body. It has also been shown that compressed gases, and under special circumstances even highly rarified gases, may be made to give a continuous spectrum.

How is it then that a candle-flame gives a continuous spectrum? One would certainly hesitate to class it either with solids or liquids, nor can its vapours be regarded as compressed or highly rarified. The continuous spectrum of the flame is in fact due to the brightly incandescent particles of carbon which float and move about in a certain region of the flame.

A gas-flame gives a continuous spectrum for a similar reason, but by a special arrangement for mixing the gas with air before it is burnt, the luminosity of the flame is enormously diminished, and the nature of the light emitted is completely altered. A special burner was devised by Bunsen for producing this sootless and non-luminous flame; it is consequently known as the Bunsen burner. The flame is described as non-luminous; but it emits a faint bluish light. The spectrum is feeble and difficult to see in any detail (see Frontispiece, line 14). It consists of certain luminous bands or flutings, to which we shall refer later on. Thus by simply making a change in the mode of burning a mixture of gas and air we have completely altered the character of the light emitted. The case shows in a striking way the need for caution in interpreting the indications of the spectroscope.

Bright line spectra of coloured flames.—A thin platinum wire, inserted into the Bunsen flame, becomes intensely heated and brightly incandescent. Its spectrum is continuous. If the wire be perfectly cleaned it does not increase the luminosity of the *flame* that surrounds it. But if the wire be dipped into sodium chloride (common salt), or in fact into any salt of sodium (*i. e.* any substance arising from the chemical combination of sodium with other

elements) and inserted into the flame, the flame becomes tinged with a more or less intense yellow luminosity. If the platinum wire is dipped into a salt of strontium and inserted into the flame, the flame becomes crimson. Calcium salts tinge it with an orange luminosity; Barium salts with green. The spectroscope analyzes the light given out by the coloured flames. For instance, in the case of common salt or sodium chloride, the spectrum at first sight appears to consist of only a yellow line. If the spectroscope is well adjusted and powerful enough, it is seen that the single yellow line is in reality two narrow lines close together, and, furthermore, that there is a faint continuous background, but under ordinary circumstances this is not at all conspicuous, and the spectrum is generally described as consisting of this double line only, the components of which are denoted by the letters D_1 and D_2. They are the celebrated sodium lines. (See Frontispiece, lines 4, 6, 7.)

Already in 1752 Thomas Melville had recognized the peculiarity in the illumination produced by a "salted" spirit-flame, but had not connected it either with sodium or with the characteristic which the spectroscope now enables us to grasp at a glance. The existence of this close double line and the absence of other lines shows us that the light emitted by the flame is to all intents and purposes a pure colour—monochromatic light—light of a definite wavelength, corresponding to a definite vibration frequency. If we are to be exact, we shall say the light consists of two components (each of a definite wavelength) differing very slightly in wavelength. Brewster in 1822 used a sodium flame in producing his monochromatic lamp. When the light from such a lamp falls upon objects, which are known to appear coloured in ordinary daylight, the colours are not apparent, and everything assumes an unwonted hue. Difference of colour depends as much upon the complexity of the light as upon the differences in

minute structure of the surfaces which appear coloured.

The luminosity which arises from a flame, when it is "fed" with *any* sodium salt or solution of the salt, gives the same spectrum consisting only of the bright D-lines. We are therefore driven to attribute the luminosity to the element common to all the salts, namely sodium.

It is curious to think how much this particular spectrum stood in the way of a rapid development of spectroscopy. Sir John Herschel in 1822 was studying the spectra of coloured flames. Fox Talbot in 1826 described the bright lines in the spectrum of the "red fire" used in theatres. W. A. Miller in 1845 was investigating the spectra of the coloured flames produced by the alkaline earths. All of these experimenters seemed to have realized that in the spectroscopic method lay a means of detecting different elements. But the persistency with which a certain pair of yellow lines appeared in all spectra, seems to have been a difficulty that stood in the way of generalizations. It was in 1856 that Swan made experiments which set on a firm basis the extraordinary delicacy of the spectroscopic test. He made out that an excessively minute trace of sodium was enough to produce the flame reaction, as it was called, and the fact that the yellow lines appeared in all spectra was thenceforward only regarded as a proof of the extraordinary diffusion of sodium through all the substances examined. It is sufficient to knock one's coat-sleeve near a Bunsen burner, or to blow the dust from a sheet of paper into the flame, to make the two D-lines visible in the spectroscope. It would be a difficult matter to procure a sample of water which did not contain enough sodium to give the yellow lines.

The memorable researches of Bunsen and Kirchhoff were published in 1859–60. One of the first results of their work was the discovery of two new

alkali metals, Cæsium and Rubidium. They found that the spectrum got by an examination of the residue of certain spring waters contained lines that could not be attributed to any known element. Bunsen was able to separate the two new metals and investigated the properties of the compounds.

The work of Bunsen and Kirchhoff gave great impetus to spectrum analysis in very varied directions, and above all it opened the way to the study of the chemistry of the heavenly bodies. (See Chaps. V and VII.)

Bright-line Spectra of vapours rendered incandescent by electrical discharges.

Many of the heavier metals could not be made to render their spectra, when their salts were put in the flame, and the spectra of such metals came to be investigated by a method which had been devised by Wheatstone in 1835.

Electric sparks.—Wheatstone observed that when electric sparks pass between pointed pieces of metal, the spectrum of the sparks exhibits many bright lines. He used sparks produced by an electrical machine, and also by an induction coil. The principle in either case is the same. Two pieces of metal are connected with the terminals of the generator of electricity. The passage of electricity between them is attended with evolution of heat in a confined space and the gas or air, together with any vapour that may be set free between the points, are raised to a state of incandescence. The nature of the spectrum obtained by discharging electricity between metal points can be varied very considerably by controlling (1) the quantity of electricity that passes, (2) the distance between the points, (3) the nature of the gas between the points, (4) the pressure of the gas, (5) the temperature of the gas, (6) the material of the metal points. In Wheatstone's experiments attention was bestowed almost entirely upon the study of the spectra produced

between pairs of points of different metals, when comparatively large quantities of electricity were suddenly discharged between the points in air under ordinary atmospheric conditions.

It is found that different metals render spectra under these circumstances with very varied readiness. Zinc and copper and iron are very easy to deal with. Silver is troublesome and requires special manipulation. In all cases the spectra exhibit bright lines which are characteristic of the metals composing the points. But there are also bright lines due to the air or other gas surrounding the points.

In the spark method the electricity is allowed to accumulate for a time (a fraction of a second), and the accumulated charge is suddenly passed between the points. The spectra obtained under these circumstances are generally called spark spectra—*e. g.* the spark spectrum of Iron.

Electric arc.—Another electrical method of producing incandescence of vapours is sometimes used, in which instead of a succession of impulsive discharges, a steady flow of electricity is maintained, namely, the electric arc. Two carbon pencils are fixed in a special holder and are connected with the terminals of some generator of electricity, either a battery of galvanic cells, or a dynamo. Electrical stress is thereby set up in the air or gas between the points; the stress increases as the points are brought closer together, but the insulating power of the air is generally sufficient in this case to support the strain. But if once the terminals are heated sufficiently, either by bringing a flame between them or by allowing them to touch for a moment so that the electricity can flow across the point of contact and thereby heat the carbon and air near that point, the discharge of electricity will take place through the air and vapour, and the points may be separated by a considerable interval without in-

terrupting the flow of electricity. The vapour is no longer able to insulate, and, further, if a small quantity of some more or less volatile salt is placed upon the glowing carbon points, the electric current passes across the electric arc, as it is called, with still greater facility. Instead of using carbon terminals and inserting salts of metals into the arc, we may use metal terminals and produce the arc between them.

If a spectroscope be pointed towards the arc, the spectrum of the vapours which are contributing to the luminosity may be seen and studied. Here again the spectra are filled with bright lines, and a vast number of substances have been examined in this way. As an instance of recent work, attention may be called to Hasselberg's examination of the arc-spectrum of the element Titanium. He has made careful determinations of the wavelengths of 729 lines in the region between the yellow of wavelength 5900 and the ultra violet of wavelength 3477, and has represented the spectrum on a map, whose total length is nearly nine feet.

A peculiar feature in the production of spectra in any of the ways described is that though we frequently arrange the conditions so that the spectra of several elements might be expected to be evoked simultaneously, yet usually the spectrum of only one is produced. For instance, when the chloride of some metal, that is, the chemical substance resulting from the combination of chlorine with a metal, is introduced into the arc, the persistent spectrum under ordinary circumstances is that of the metal; but if the conditions are changed the spectrum of chlorine can also be made visible. Thus if the points between which the electricity passes be enclosed in a glass tube or vessel properly constructed, so that the points can be surrounded by any gas at any desired pressure, then lines characteristic of the gas used as well as those of the metal points may be evoked; and

further, by proper manipulation, the spectrum of the gas alone, without any lines due to the metal terminals, may be obtained.

Bright-line spectra produced by electric discharge through rarefied gases.—It is found that as the pressure of the gas is reduced, its insulating properties are diminished and a discharge can be made to pass through such rarefied gas, and it is accompanied by luminosity of the gas.

Under these circumstances Nitrogen becomes luminous with a glow whose colour depends greatly on the pressure of the gas; Hydrogen gives a crimson glow under certain circumstances, and white under other conditions; Chlorine, a silvery blue glow. Each of these examined with the spectroscope

FIG. 31.

renders a characteristic spectrum, and it is clear that the surrounding gas rather than the nature of the metal terminals is the thing that determines the character of the spectrum.

Fig. 31 represents a form of tube devised by Plücker and manufactured first chiefly by Geissler for exhibiting the luminosity of rarefied gases. The terminals in a hydrogen tube are generally made of aluminium attached in a special way to a small platinum wire partly surrounded by glass and fused into the end of the wider part of the tube. The terminals are connected with an induction coil and electrical discharges are passed through the gas between the terminals. The brilliancy of the discharge is increased by the constriction of the space through which the discharge passes, but it is important not to constrict the space around the terminals. Such a tube, with its capillary constriction and with

its rarified gaseous contents, is called a Plücker tube or a Geissler tube.

Spectra of different orders.—The spectra of the gases seen in Geissler tubes are bright line spectra, but Plücker and Hittorf called attention to the very remarkable fact that certain gases were capable of emitting, each of them, two or more entirely different spectra according to the conditions of temperature and pressure to which they were exposed. The two "orders" of spectrum emitted by Nitrogen are represented in Fig. 32 (where dark strokes mean bright lines). The entire dissimilarity will be at once noticed. In the one case we see what is called a fluted spectrum, consisting of groups of bright lines arranged with curious irregular regularity; in the other case

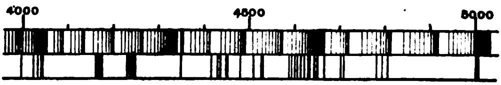


FIG. 32. (See also Frontispiece, line 13.)

we see a spectrum quite comparable with the spectra of the metals, simply a bright line spectrum.

Banded, fluted, or cannelated spectra.—An enormous number of substances are now known to give fluted spectra. Many of the carbon compounds (such as cyanogen, hydrocarbons, and carbonic oxide) give spectra of this kind. Thus the blue part of the flame of a candle, and also the "non-luminous" flame of a Bunsen burner, both give a fluted spectrum. Further, many fluted spectra have been observed under circumstances that render it extremely probable that they must be attributed to compounds of metals with non-metallic elements; such as, for instance, the spectrum derived by Liveing from magnesium in the presence of hydrogen, and attributed by him to the compound Magnesium hydride. On the other hand, quite recently, Eder and Valenta have observed a fluted or banded spectrum which

they attribute to pure mercury vapour and not to the vapour of a compound of mercury.

ABSORPTION-SPECTRA.

In the case of each of these varieties of spectra hitherto described, (1) continuous spectrum, (2) bright line spectra, (3) banded, fluted, cannelated spectra, we have dealt with the *emission of radiations* of definite wavelength or frequency of vibration.

Absorption lines.—When we observe the spectrum of the sun, or of many of the stars, we find that the spectrum may be described as a continuous spectrum, from which a number of narrow lines are omitted. The lines consequently appear dark on a bright ground. These are called absorption lines.

Wollaston in 1802 had already observed these black lines in the bright spectrum of the sun. Fraunhofer in 1814 mapped 576 of them, and from his remarkable work of examination of the solar spectrum, the black lines have been called Fraunhofer's lines, and the letters which he used to designate the more prominent lines are still employed. (See Frontispiece, line 2.)

The bright line spectra are made up of bright lines on a dark background, and the lines are the result of *radiation* of light of definite wavelengths. The solar spectrum is made up of dark lines on a bright background, and the lines are due to the *absorption* of light of definite wavelengths. (See Chap. V.)

Another example of "line-absorption," such as is seen in the solar spectrum, is afforded by a beautiful experiment made by Bunsen and Kirchhoff. They placed a small piece of metallic sodium in a glass tube, and having exhausted the air from the tube, sealed the tube hermetically. This was interposed between a candle-flame and the spectroscope, so that the light could only enter the slit after passing through the tube. When the tube was heated even slightly, there appeared two narrow dark lines close

together in the yellow part of the continuous spectrum of the flame. When the tube was cold, these absorption lines were not seen. The dark lines appeared in exactly the same part of the spectrum as the bright lines seen in a sodium flame. Thus sodium vapour absorbs light of the same wavelength as that of the light that incandescent sodium vapour emits.

Continuous absorption.—If the flame of a candle is spectroscopically examined through a piece of coloured glass, we are able to see at a glance to what the colour of the glass is to be ascribed. The candle, we know, emits lights of all colours, but if a piece of red glass is interposed, the spectrum shows that the green light has been cut out by the glass, as well as a good deal of the yellow and blue and violet; red glass *absorbs* green light, is opaque to it, but transparent to red light and semi-transparent to violet, blue and yellow light. Some sorts of red glass are nearly completely opaque to all light except the red and orange. This glass would be suitable for the window of a photographic dark room; and with a spectroscope we can at once tell which of two samples of red glass is best suited for a dark-room window.

The absorption of the green light by red glass eliminates from the continuous spectrum of the candle a broad band, and we speak of this as an absorption band. We are at once struck by the difference between the narrow lines seen in the absorption-spectra of some vapours and the broad bands seen in the absorption spectrum of red glass. The broad absorption band produced in the green by red glass is of the nature of what may be called continuous absorption, inasmuch as no defined lines are seen in it. An absolutely opaque body gives a complete continuous absorption spectrum; it absorbs light of every wavelength.

An examination of various coloured, transparent, solid, liquid and gaseous substances brings to our knowledge as great a variety in the nature of the

absorption produced by these bodies as in the nature of the light emitted by incandescent substances. Some of the most interesting absorption spectra are given by coloured gases and vapours. Thus the gases Chlorine, Bromine and Iodine, have each of them very marked spectra. Janssen, looking at a bright source of light through long columns of oxygen and of water vapour, has been able to see the characteristic absorption bands and lines produced by these substances.

Compound vapours are also capable of producing absorption spectra of a banded or fluted nature of the same character as those emitted by such compound vapours when they are rendered incandescent by proper means. Thus Liveing has observed the banded spectrum of cyanogen "reversed." Paschen has studied the absorption spectrum of carbonic oxide.

Summary of the Varieties of Spectra.

Emission-spectra.

i. Continuous spectra, as emitted by incandescent solids and liquids, and also by compressed gases and even highly rarefied gases.

ii. Bright-line spectra, as emitted by incandescent vapours and gases.

iii. Bright-banded or fluted spectra, as emitted by incandescent vapours of certain compounds, and in a few cases by certain elements, such as nitrogen, mercury, etc.

Absorption-spectra.

iv. Absorption-band spectra with broad absorption bands, such as may be seen by viewing "a continuous" source of light through certain coloured transparent solids, liquids, gases or vapours.

v. Absorption-line spectra filled with dark narrow

lines, such as may be seen in the spectra of the sun and of many of the stars, and also in certain gases and vapours held in front of a "continuous" source.

vi. Absorption-banded or fluted spectra with dark flutings and bands, such as may be seen by viewing a "continuous" source through certain transparent liquids and gases and vapours.

We see then that while the spectroscope analyzes the sample of light received by it, yet accumulated experience is needed before we can be certain how to interpret the appearances presented as the result of the analysis. Thus when we look with a spectroscope at a flame made luminous by the incandescence of different chemical substances, we see a complicated spectrum; we apply to what we see the analysis of experience, and can say that some of the lines belong to the spectrum of the flame, others to the "spectrum of sodium," others to the "spectrum of calcium," and so on. We thus come to attach a special significance to the word spectrum, and use it to describe that array of lines which is characteristic of some pure substance, on the assumption that the pure substance can be made incandescent independently of the presence of other kinds of matter.

CHAPTER V

THE SOLAR SPECTRUM

A PORTION of the solar spectrum is represented in Plate IA, which is a photographic reproduction of a photograph.

The bright parts represent the light of various vibration-frequencies which reaches us; the dark

lines by their position in the spectrum indicate the frequencies of the light that has failed to reach the spectroscope, either because light of these frequencies could not pass through the vaporous surroundings of the sun, or else because the light was absorbed in our own atmosphere.

This concise description of the interpretation of the solar spectrum sums up in the most general terms the evidence that has been slowly accumulated by a very large number of workers. The result of their work is that we are able to infer from the dark lines in a spectrum like that of the sun the existence of certain elements in the sun with as much certainty as we can from the bright lines in the spectrum of an electric spark between metal points infer what the nature of the metal composing the points is. The present chapter is to give an account of the development of this mode of analysis which has enabled us to investigate the chemistry of the heavenly bodies, and to infer much as to the physical state of their surrounding atmospheres.

It appears that Newton in his classical experiments did not notice, or at any rate did not record that he noticed, the fine dark lines that form such a striking part of the solar spectrum as we now know it. Wollaston was the first who noticed the lines; he recorded his success in 1802. He viewed the spectrum of the sun by looking through a prism at a narrow and distant slit through which a sunbeam passed, the prism being held in the sunbeam with the refracting edge parallel to the slit.

In 1814 Fraunhofer made his observations and map to which we have already referred (page 56). He satisfied himself that the lines were to be seen with all kinds of prisms, whatever their material might be, glass, crystal, or liquids contained in prism-shaped vessels. The lines therefore could not be due to the prisms used. He examined the moon, the planets, sky, cloud and terrestrial objects illuminated by sun-

light, and found that their spectra contained the same dark lines as he had observed in the sunlight. He studied the spectra of the stars, and here at last he found differences. They all gave, it is true, the colours in the same order, but the dark lines were differently placed or of different intensity. The spectra of the stars were different from each other and from the sun. The lines in the solar spectrum therefore could not be due to the earth's atmosphere, though it is true that Fraunhofer found more lines in the spectrum when the sun was near the horizon than when it was overhead.

After Fraunhofer's work followed a considerable interval, in which no advance was definitely made in our understanding of the solar spectrum. It is not until after 1840 or even 1850 that there is much to add to the history of the subject.

The celebrated D-lines of the solar spectrum play the most important *rôle* in the history. In the part of the spectrum between the orange and the yellow, there are two strongly marked dark lines which Fraunhofer indicated by the letter D in his map of the solar spectrum published in 1814. Fraunhofer observed in the flame of a candle a double bright line in that part of the spectrum, in which the solar spectrum showed the double *dark* line D. This coincidence was corroborated by the careful observations of other investigators, but no further advance was made towards an explanation of the coincidence or even towards realizing that it was more than a fortuitous occurrence until 1849, when Foucault published an account describing the result of a prismatic analysis of the voltaic arc formed between charcoal poles. It attracted the attention of only a few investigators, though it was a result of the highest importance.

In 1860, just after Kirchhoff's communication on Fraunhofer's lines had been brought before the Berlin Academy (October 1859), Professor Stokes forwarded to the *Philosophical Magazine* (March 1860) transla-

tions of both Foucault's and Kirchhoff's communications. These make the matter so clear that we venture to transcribe them:—

Foucault, referring to the voltaic arc formed between charcoal poles, says: "Its spectrum is marked, as is known, in its whole extent by a multitude of irregularly grouped luminous lines; but among these may be remarked a double line situated at the boundary of the yellow and orange. As this double line recalled by its form and situation the line D of the solar spectrum, I wished to try if it corresponded to it; and in default of instruments for measuring the angles, I had recourse to a particular process. I caused an image of the sun, formed by a converging lens, to fall on the arc itself, which allowed me to observe at the same time the electric and the solar spectrum superposed; I convinced myself in this way that the double bright line of the arc coincides exactly with the double dark line of the solar spectrum. This process of investigation furnished me matter for some unexpected observations. It proved to me, in the first instance, the extreme transparency of the arc, which occasions only a faint shadow in the solar light. It showed me that this arc, placed in the path of a beam of solar light, absorbs the rays D, so that the above-mentioned line D of the solar light is considerably strengthened when the two spectra are exactly superposed. When, on the contrary, they jut out one beyond the other, the line D appears darker than usual in the solar light, and stands out bright, in the electric spectrum, which allows one easily to judge of their perfect coincidence. Thus the arc presents us with a medium which emits the rays D on its own account, and which at the same time absorbs them when they come from another quarter. To make the experiment in a manner still more decisive, I projected on the arc the reflected image of one of the charcoal points, which like all solid bodies in ignition gives no lines (only a continuous spectrum),

and under these circumstances the line D appeared to me as in the solar spectrum."

Thus Foucault had learnt the secret of the solar spectrum in 1849. Kirchhoff discovered it again in 1859. Meantime Stokes had been one of the few who had realized the importance of Foucault's work, and had given the interpretation of the solar spectrum which we now accept, *i.e.* if a vapour is capable of emitting light of particular wavelengths, it is capable of absorbing light of the same wavelengths, and the dark lines on the solar spectrum are the result of absorption by the vapours surrounding the sun. Kirchhoff in 1859 and the following years threw himself heart and soul into the study of the conditions under which a vapour may in one and the same state be capable of emitting bright lines when its own luminosity is analyzed, and of producing the appearance of dark lines in the continuous spectrum of a bright source which sends light through the already luminous vapour. He found that in the latter case the dark line *appears* dark in comparison with the brighter light on either side of it, although it is in reality bright.

These experiments made it clear that the existence of sodium vapour could be detected either by bright lines in the flame spectrum or by dark lines in a continuous spectrum. In the first case the vapour is in a state of incandescence and emits light of certain definite wavelengths; in the second case, it is in a state in which it absorbs light of just the same wavelengths, and when light coming from a suitable source, whose spectrum is continuous, passes through the absorbing vapour, dark lines appear in the spectrum as a necessary consequence of the absorption.

It should be realized that the spectroscopic evidence affords proof of the presence, but not necessarily of the absence of substances. If, for instance, the dark sodium lines are not seen in the spectrum, we are at liberty to interpret this by saying either that there

is no sodium present or that if sodium is present it is not in a state in which it is capable of absorbing the characteristic light.

Kirchhoff's communication in 1859–60 attracted far more general attention than did Foucault's in 1849, probably because it was published about the same time as Bunsen and Kirchhoff's joint work on *Chemical Analysis by Spectroscopic Observations.* Bunsen's discovery of the two new alkali metals, Cæsium and Rubidium, roused the greatest interest in the new mode of analysis for terrestrial purposes; and Kirchhoff's work on the solar spectrum made it clear how we could study the chemistry of the sun and the stars.

Kirchhoff arrived at his conclusions relative to the chemical composition of the sun by a comparison of the bright lines seen in the spectra of various metals, and the dark lines seen in the solar spectrum. He paid special attention to the identification of the bright iron lines with dark solar lines. Kirchhoff saw the necessity of making an estimate of the chances of fortuitous coincidences. If there are, let us say, 60 bright iron lines in a certain region of the spectrum examined, it may be possible to find an apparent coincidence between each one of the bright lines and one of the very numerous dark lines in the sun; and the apparent coincidence of each of the 60 lines with a dark line may be in a sense a mere work of chance. Kirchhoff estimated with what degree of exactness he could determine a "coincidence," and arrived at the conclusion that the probability that such a series of coincidences should occur *by chance* is less than $(\frac{1}{2})^{60}$, that is, $\frac{1}{2} \times \frac{1}{2} \times \ldots \times \frac{1}{2}$ (sixty times), and therefore less than one in one million million million. If in addition to coincidence in position there is a similarity in the appearance—breadth and intensity—between the bright lines and the coinciding dark lines, the probability just referred to is rendered still smaller. Kirchhoff therefore concluded, "Hence

this coincidence must be produced by some cause, and a cause can be assigned which affords a perfect explanation of the phenomenon. The observed phenomenon may be explained by the supposition that the rays of light which form the solar spectrum have passed through the vapour of iron, and have thus suffered the absorption which the vapour of iron must exert." Kirchhoff adduced reasons for believing that the iron vapour is in the solar atmosphere and not in the earth's (see page 75).

Research was thus inaugurated which went on with leaps and bounds: and the present state of knowledge enables us to assert that out of more than 75 elements known to chemists, there are 37 certainly present in the sun, 8 are doubtful, 15 appear to give no sign of their presence, the remainder are still to be tried. Such is the result based on the report which Rowland, under whose direction the most exact work has been carried out in the Johns Hopkins University in America, published in 1891.

Rowland later on published Preliminary Tables of Solar Spectrum Wavelengths. This contains the wavelengths (each to 7 significant figures) of about 20,000 lines between the wavelengths 2975 and 7331.

Plate IB shows the coincidence between the bright lines in the spectrum of iron and the dark lines in the spectrum of the sun in a comparatively small region of the spectrum, the same region as in Plate IA.

Rowland recognized more than 2000 iron lines in the spectrum of the sun.

So far as I have described Kirchhoff's work up to this point, the matter seems quite simple. The fact was established by observation:—dark lines in the solar spectrum correspond in position and relative intensity with bright lines in the spectra of metallic vapours in flames and electric sparks. The matter was, however, complicated by considerations suggested by some other observations which he made and which had escaped the notice of Foucault.

"The Drummond light (oxyhydrogen limelight) requires, in order that the lines D should come out in it dark, a salt-flame of a lower temperature. The flame of alcohol containing water is fitted for this, but the flame of Bunsen's gas-lamp is not." Kirchhoff showed that the condition needed for "reversal" of lines was that, behind a flame which emits a bright-line spectrum, there must be placed a "continuous" source of light of a *sufficiently* high temperature. The interpretation to be put on that word "sufficiently" was the question that occupied Kirchhoff's mind. The solution involves considerations beyond the scope of this primer. It is enough to say that we believe that in the sun and stars there is a photosphere or layer of incandescent matter which gives a continuous spectrum bright enough to make the metallic lines (due to the superincumbent vapours) look *relatively* dark. (See page 107.)

CHAPTER VI

INCREASE OF THE POWER OF A SPECTROSCOPE

Most people who are not accustomed to astronomical observations are disappointed the first time they look through a large telescope. They come expecting that a large telescope will show a large image of a star, and exclaim, "How bright it is, but how small!" The exclamation may be taken as high testimony to the success of the optician. A star is the nearest approach to a *point* of light that we know; not because the star is so small, but because it is so remote. It is a result of the undulatory nature of light that the image which a perfect telescope gives of a point of light is not a point but a very small, more or less diffused circular patch of light surrounded by rings of rapidly diminishing intensity. The larger the object-glass of the telescope is made, the more

light does it collect and the smaller does the patch of light become, and the more is the light concentrated to the middle of the patch. A large telescope makes a star look brighter and smaller than a small telescope. Hence a close double star like β Delphini, which in a small telescope looks like a single star, appears in a large telescope as two distinct stars. The small telescope gives two overlapping patches, each having dimensions comparable with the apparent separation of the centres of the two star-images (Fig. 33); a simple increase in the magnifying power will avail nothing, for the object-glass forms two overlapping images, which no eyepiece can "resolve," however much it magnifies.

FIG. 33.

The increase in the diameter or aperture of the object-glass brings about a real increase of the "resolving power" of the telescope in virtue of the diminution in the size of the images produced. Our way then is clear when we want to get a more powerful telescope. How shall we proceed, when, after the first survey of spectra has been made, it becomes desirable to construct a spectroscope of higher power?

Suppose, for instance, that we want to decide whether a certain line in the spectrum is single or double, then the spectroscope used should be capable of giving very narrow images of the slit and also of showing the colours in the spectrum widely separated, that is, highly dispersed. We have two ways of improving matters in the spectroscope; (i) either we may use larger object-glasses, and also larger prisms of the same angle as before—this will make the images of the slit narrower, but will not affect the angular dispersion of the colours—(ii) or we may keep the object-glasses the same size as before and increase the number of the prisms or the refracting angle of the prisms, or use a more dispersive kind of glass for the prisms—this will separate the colours more, but will not affect the narrowness of

the image of the slit. It is, of course, open to us to adopt a combination of these two modes of alteration.

Lord Rayleigh has pointed out the principle that should mainly guide us when we wish to design a spectroscope or to push the instrument to the limit of its power. He discovered that, when the kind of glass to be used for the prisms has been chosen, the resolving power of a spectroscope depends only on what may be called the effective length of the base of the prisms, and not on the way in which the base is arranged; the result is the same whether one large prism is used or many small ones, so long as the total length of the base is the same. We may illustrate his remarkably simple result by taking special cases.

Figs. *A*, *B*, *C*, *D*, *E* on the folding plate (p. 72) represent, on the same scale throughout, five spectroscopes of equal resolving power; if one instrument shows a very close pair of lines in the spectrum as just resolved into two lines, all the other instruments will do so equally well. In each of the figures the base of the prism is indicated by a dark line, and the intention is to show instruments in which the total length of the effective prism-bases is the same; the prisms being all of the same material.

When a beam of light passes through a prism the *effective base of the prism* is the difference in thickness of glass traversed by the two rays which form the extreme flanks of the beam. If a prism is made with a sharp refracting edge and the limiting rays on the two flanks of the transmitted beam pass close to the refracting edge and close to the base respectively, as indicated by the dotted lines in Fig. *A*, then the effective length of base coincides with the actual length of base. If the prism, as in Fig. *G*, is not made with a sharp refracting edge, or if the limiting rays, as in Fig. *F*, do not pass close to the edge, then the effective base is equal to the difference in thickness traversed by the limiting rays; this is indicated

in *G* and *F* by the dark lines which do not extend the whole lengths of the actual bases of the prisms.

For the sake of simplicity in explanation, we shall make the following assumptions:—

(1) The prisms are all set for minimum deviation of the same colour in the spectrum.

(2) The slit and eyepiece are the same in all cases.

(3) The slit is exceedingly narrow.

(4) The light entering at the slit spreads out enough to "fill" the collimator lens (see p. 44), and the prisms and camera or telescope lenses are large enough in every case to utilize the whole of the beam that comes from the collimator.

(5) The object-glasses in *A*, *B*, *C*, and *D* all have the same ratio of diameter to focal length, *i. e.* where large object-glasses are used, the focal lengths are correspondingly great.

(6) In each spectroscope, *A*, *B*, *C*, *D*, the collimator and telescope have equal lengths; but in *A* with one prism, the telescope is twice as long as in *B* with two prisms, and four times as long as in *C* with four prisms.

With the limitations stated, we can assert that the appearance in the field of view is the same in all particulars, scale, purity, and brightness, in every case. Without any such limitations, we can assert that the resolving power is the same in every case.

Let us now compare spectroscopes *A* and *B*, remembering that we regard the spectrum as the result of the close juxtaposition of parallel images of the slit in various colours.

In *A* we have one prism, a long telescope and large object-glasses. The large object-glasses give narrow images of the slit, for the same reason as a large telescope gives a small image of a star. The single prism disperses the colours through certain but not great angles. The long telescope shows the dispersion of the colours on a large scale.

In *B* the smaller object-glasses would give images

of the slit twice as broad as in *A*, if it were not that the telescopes were shorter and that this diminution in length, under the condition that the ratio of diameter of object-glass to focal length is the same, brings it about that the images are just of the same *linear* width as in *A*. The two prisms disperse the colours through angles twice as great as in *A*, but the shorter telescopes bring it about that the linear scale is just the same as in *A* (see p. 36). Hence the spectra observed in the eyepiece in *A* and *B* are exactly alike, the width of the monochromatic images of the slit being the same, and the distance between any two colours in the focal plane of the telescope being the same in the two cases.

Similar considerations may be applied to the case *C*. Doubling the number of prisms and halving their size, leaves the total length of base the same. Doubling the number of prisms doubles the angle between two colours, but halving the size of the prisms halves the width of the beam transmitted, and thereby also doubles the angular width of the image of the slit. Hence the relation between the width of the image of the slit and the separation of the colours remains the same.

We take this opportunity of introducing certain technical expressions in comparing the cases.

The *angular dispersion* is twice as great in *B* as in *A*, for two prisms are used in *B*. Each prism produces the same angular dispersion [*e.g.* the red and the blue pass out in directions inclined to one another at an angle of (say) 3°], because the prisms are all of the same angle and material, and the colours which are separated by the first prism are again separated still further by the second, the total separation of two colours being twice as great for two prisms as for one.

The *linear dispersion* is the same in all the cases, *A*, *B*, *C*, and *D*, for the red and blue images of the slits are separated in the focal planes of the telescopes by the same linear distance in each case.

The *purity* of the spectra is the same in all four cases, that is to say, the overlapping of the neighbouring colours is the same, for that depends on the width of the monochromatic images of the slit relative to the separation of neighbouring colours.

The *resolving power* of the spectroscopes is the same; for the instruments could resolve equally close pairs of lines, differing very slightly in wavelength.

It is to be noted that "*resolving power*" relates to an instrument, while "*purity*" relates to the spectrum.

We may define the "resolving power" of a spectroscope as that power, depending on the construction, in virtue of which a spectroscope can separate two colours that differ very slightly in wavelength, by showing the two corresponding images of the slit "resolved" as a double line, and not as a single line blurred by the overlapping of the components. We get an indication of its magnitude from the smallness of the difference between the wavelengths of lines which can just be resolved by the instrument; and when we say, for instance, that the resolving power of a certain spectroscope is 1000, we mean that it can resolve two lines which differ in wavelength by $\frac{1}{1000}$th of the wavelength of either. Thus the yellow sodium lines D_1 and D_2 have wavelengths 5896 and 5890 tenthmetres, and the difference, 6 tenthmetres, is close upon $\frac{1}{1000}$th of their wavelengths. These lines can only be resolved by a spectroscope which has a resolving power of 1000, and Lord Rayleigh has shown that in order to attain this power, if the prism is made of ordinary dense flintglass, the base of the prism must be at least 1 centimetre long. In refined work, such a resolving power is very small.

We may define the "*purity*" of a spectrum as that quality of a spectrum which is improved by diminishing the overlapping of monochromatic images of the slit in neighbouring colours. If the slit of a spectroscope is wide, the images of the slit must also be proportionately wide, and the overlapping of the wide

images clearly impairs the purity of the spectrum. Hence by making the slit narrower we improve the purity of the spectrum given by a spectroscope.

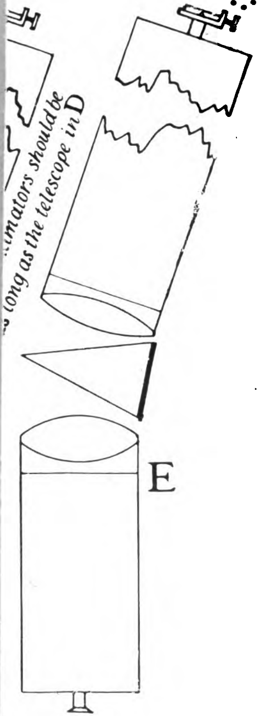
Let us now compare the spectroscopes represented in Figs. *A* and *D*. Here each of the spectroscopes is a single-prism instrument, but the refracting angle is less in *D* than in *A*, whilst the object-glasses of *D* are larger. Under these circumstances the spectra given by the two instruments appear exactly alike, when the same slit and eyepiece are used. The use of a smaller refracting angle (and consequently smaller dispersion of the colours) is, under the condition of equal bases, entirely compensated by the necessarily greater width of the beam (and consequently narrower image of the slit).

Lastly let us compare the cases represented in Figs. *D* and *E*. The prisms and collimators are supposed to be identical, but the camera in *E* has been so made that the focal length is shorter than in *D*, whilst the diameter of the lens remains undiminished. Here all that happens is that the linear scale of the spectrum in the focal plane of *E* is smaller than that in *D*, just in the same ratio as the focal lengths of the cameras in *E* and *D*. The spectrum is much brighter; but the purity remains as before, because the relation between the width of the image of the slit and the separation of the colours has not been changed.

Lord Rayleigh's result is that, when the material of the glass has been chosen, the resolving power of a spectroscope depends solely on the length of the *effective* base of the prism-system.

All the spectroscopes represented in the figure are of the same power. Suppose we wish to double the power.

In the case of *A*, the single-prism instrument, we might use a prism of twice the size, but then we should have to double the size of the object-glasses of the camera and collimator. It would be cheaper to add a second prism; we should then have an instrument identical in *form* with *B*, but with each *dimension* doubled.



[*To face page* 72.

In the case of C, the power may be doubled by doubling the dimensions. An increase in the number of prisms may lead to difficulties in placing the collimator and the viewing telescope in such a way as not to interfere with one another's action. Many very ingenious devices have been invented for utilizing more numerous prisms.

It will be realized that the use of prisms of small angle involves the use of comparatively large object-glasses; the use of prisms with angles larger than about 62° involves the loss of a considerable proportion of the incident light by oblique reflexion at the prism surfaces.

With respect to material for the prism system, it is enough to say that the use of the heavier glasses is of advantage in increasing the resolving power of an instrument, for their dispersive powers are greater; but they are generally more absorbent of light, especially at the blue end of the spectrum. When the ultra violet part of the spectrum is to be studied, glass is found to be too absorptive, and quartz prisms and object-glasses are then used. When the infra ultra red part of the spectrum is to be studied, glass is again found to be too absorptive, and rock salt or fluor spar prisms and object-glasses are then used.

CHAPTER VII

THE SPECTRA OF THE STARS

The application of spectrum analysis to the light of the stars was carried out first in the beginning of the nineteenth century, nearly fifty years before the work of Bunsen and Kirchhoff. The pioneer in the work was the optician Fraunhofer, who after his investigation of the solar spectrum (page 60) sought

for some hint of explanation of the dark lines and set himself to examine the spectra of the stars and planets. He used an ordinary telescope, placing in front of its object-glass a prism of such dimensions that it embraced a beam of starlight large enough to fill the whole object-glass (four inches in diameter) of his telescope. This form of instrument has been called a prismatic camera, and the large prism fixed in front of the object-glass is usually known as an objective prism. When it is pointed properly towards a star, so that the starlight, after passing through the prism, travels down the tube of the telescope, the spectrum can be viewed with an eyepiece. The star takes the place of the slit in the ordinary spectroscopes and the universe is the collimator, rendering the rays parallel to one another, in consequence of the distance of the star. The telescope gives, instead of a single image of the star, a multitude of coloured images forming a linear spectrum, that is, a spectrum which is a long narrow line of light, blue at one end, red at the other; its width is no greater than the diameter of the image of the star. Under these circumstances "dark lines" in the spectrum would really be dark dots and peculiarly difficult to see; hence a special eyepiece is used to increase the apparent width of the narrow spectrum enough to make the characteristics of the spectrum visible without unnecessary loss of light.

With such an instrument Fraunhofer investigated the spectra of the brighter stars and found that some of them, such as Arcturus (α Bootis) and Capella (α Aurigæ), and also the planets Mars and Venus, had spectra similar to that of the sun. The spectra of Sirius and Castor, instead of exhibiting numerous narrow lines like those visible in the solar spectrum, showed only three broad lines of absorption, one in the green and two in the blue. These are now known to be the broad absorption lines of hydrogen.

He also found that whereas in Capella, Betelgeuse, Procyon and Pollux the dark D lines were conspicuous, he could not see them in the spectra of Sirius and Castor. Fraunhofer recognized this difference as a proof that it was not the earth's atmosphere which produced the dark lines.

Within a year or two after Kirchhoff's work on the chemistry of the sun, Huggins and Miller boldly attacked the subject of the chemistry of the stars, making a series of minute observations of the light of the stars with a slit spectroscope attached to the eye-end of an astronomical telescope which enabled them to make comparison of stellar spectra with the spectra of terrestrial elements. About 100 stars were examined in detail in this way, and the result of the work was to show that many lines in the spectra of known chemical elements on the earth were represented by dark absorption lines in the spectra of the stars. Thus was established the fact that these elements are widely diffused throughout the universe. From the general similarity of the spectra of many stars to that of the sun, there could be left no doubt that in a broad sense the sun differs from such stars only in its comparative proximity to us.

Almost at the same time as Huggins' earliest work, a study of the spectra of different stars was carried out by Rutherford; and Father Secchi, taking up the work in Italy on the same lines as Fraunhofer had originated in Munich, observed the spectra of 600 stars and later of more than 4000 stars. He found only four types of stellar spectra amongst all these stars.

Plate II indicates the nature of each of Secchi's four types of stellar spectra.

The first type is that of stars whose light is white or bluish like that of Sirius or Vega. The spectrum is rich in violet rays and exhibits broad and intense lines attributed to the absorption produced by hydrogen. The metallic lines are relatively faint, but are nevertheless visible on careful examination.

Of the second type of spectrum that of the sun may be taken as representative, filled with innumerable dark lines, most of them narrow, none of them showing the excessive breadth of the hydrogen lines exhibited by the stars of the first class, except perhaps two lines denoted by Fraunhofer's letters *H* and *K*, close to the limits of visibility at the violet end of the spectrum and now commonly attributed to calcium. The stars of this class are of yellow hue.

The third type is presented by a large number of red stars, many of which are variable. As a notable instance, we may take Betelgeuse. The characteristic of the spectrum is the existence of a considerable number of flutings, in each of which the distribution of intensity of the light is such that the brighter end lies nearest to the red end of the spectrum.

The fourth type is afforded by stars that are mostly notable as deep red stars, but no very bright example can be given. In their spectra the characteristic is again flutings, but the distribution of intensity of the light in each fluting is in a reverse sense to that described in the third class; each fluting is brighter at the end nearest to the violet end of the spectrum.

The spectra corresponding to the last two classes show a very large number of fine absorption lines similar to those seen in the solar spectrum, but the characteristic of the two types is the apparent superposition of these broad flutings on the spectrum of narrow lines. At first sight it is not clear whether the flutings should be regarded as bright flutings superposed on a comparatively faint spectrum, or as absorption flutings in part obliterating a relatively brighter spectrum. Fowler has recently shown that in type III they are absorption flutings due to titanium oxide.

On Pickering's suggestion, a fifth type of stellar spectrum is generally recognized, containing bright lines.

The result of Secchi's work was to show that there were many and marked differences between the spectra of the stars, and though various spectra were found of such intermediate nature that one might well hesitate about assigning them to one type or another, yet practically four types were sufficient for a preliminary classification. Then the usual history of all classifications began. At first the existence of definite types is the interesting point; for it may mean that bodies tend towards certain states which are more permanent than others. Then the discovery of transitional forms becomes the interest; for it suggests a process of evolution of one type from another and leads to wonderment about the order in which the types should be most properly arranged. And finally when we realize that our sun is one of the great host of stars, there comes the relentless answer which our accumulated studies of the stars must give to the question, Is the sun, the centre of our own system, waxing or waning?

We may look at the subject in another way. We see these countless suns, which we call stars, and find them in different states as their spectra indicate. We may ascribe the difference in state to difference in material, and should then make bold to expect to find stars distributed in the universe more or less according to the nature of their material; for if the spectroscope shows that stars exist that contain substances unknown in our system, may it not be that these unknown substances belong to one part of the universe and not another? Here then the distribution of peculiar stars in the universe becomes the leading interest.

Again we may look at the matter in yet another way. Having searched among the stars, as they now exist, for indications that suggest that one star is farther on in its life than another, we may then try to gather from the relative numbers of stars in

the various types some idea as to whether the universe as a whole is in its youth, in middle life, or in declining age.

In its inception Secchi's work was avowedly intended as a provisional survey of spectra, but he came later to regard the order of his types as representing the progressive physical development.

In 1874 Vogel set forth a new method of classification with the following words—"A rational classification of the stars according to their spectra is probably only to be obtained by proceeding from the standpoint that the phase of development of the particular body is in general mirrored in its spectrum." The condition for the admission of a star into the first class was that the candidate should be a star in such a high state of incandescence that the metallic vapour contained in its atmosphere could exert an exceedingly slight absorption. Vogel's second class consists of stars whose atmospheres, like that of the sun, reveal the presence of metals by strong absorption lines in the spectrum. The third class contains stars whose temperature of incandescence is so far diminished that the association of the elements to form compounds has taken place in their atmosphere so that the chemical compounds prove their existence by the formation of absorption flutings in the spectra.

Vogel thus deals with three classes of stars, and in each class he has subdivisions for peculiar or intermediate cases. Development in the direction of falling temperature is alone taken account of, Vogel's term incandescence being seemingly an indication of the temperature of strata below the vaporous surface of a star.

In Lockyer's classification, on the other hand, account is taken of the possibility of a development involving first a rise in temperature and then a fall in temperature. The mathematical investigations of August Ritter and of Homer Lane Fox into the consequences of certain physical conditions in the

life history of gravitating masses of gas have disclosed the idea that in part of the history temperature must be rising, and that at the present moment of time there must be many stars which must be regarded as rising in temperature. Lockyer's view is that the sun is to be classed among stars which have already cooled considerably.

Sir William and Lady Huggins arrange certain typical stars, whose spectra they have examined in detail over a very wide range, especially in the ultra violet, in a definite series suggesting the order of evolution. They take the view that the sun which comes near the middle of their list is at the highest temperature.

Pickering adopted a provisional classification for the photographic spectra of 10,000 stars which forms part of the work undertaken at the Harvard College Observatory to commemorate Henry Draper, an American astronomer and physicist, cut off in his prime. The catalogue, which has been called the Draper Catalogue of stellar spectra, contains a list of 10,351 stars, and is a great achievement as a first photographic survey of the spectra of the stars, undertaken and completed in a single observatory. The system of classification illustrates the efficacy of photographic methods; for it involves the use of seventeen distinctive symbols, instead of Secchi's four. Pickering has also recently published classifications of the brighter stars, carried out under his direction by Miss Maury and by Miss Cannon. In these no less than 31 classes are recognized.

Many remarkable results have been obtained by Pickering and his assistants in the study of the photographs taken as part of the Draper Memorial. Mrs. Fleming discovered several spectra in which there are bright hydrogen lines; and from the known variability in brightness of many of the stars which possessed this spectroscopic peculiarity, it seemed a justifiable generalization to expect variability in all

such stars. Thus when a bright-lined spectrum was discovered in a star which had not hitherto been recorded or suspected as a variable, attention was directed to the comparison of the brightness of this star with that of its neighbours, and the result of this work has nearly always been the discovery of variability, in a comparatively long period. Furthermore, as an immediate result of collecting material relating to the spectra of stars in all parts of the sky, Pickering was able to discover that all these long-period variable stars with bright hydrogen lines in their spectra were distributed in a particular zone of the heavens, which coincides very nearly, if not exactly, with the Milky Way.

McClean also pointed out, as one of the results of his own photographic survey of the spectra of the brighter stars in both hemispheres, that the stars which are notable for having certain lines, known as helium lines (p. 104) in their spectra, are gathered together in certain regions of the sky (as for instance in the constellation of Orion).

Pickering has studied the distribution of the spectral types generally in the sky. Dividing up the surface of the sky, for which he had collected the material, into 48 parts of equal extent, he has compared the numbers of stars of the various types, and arrived at the following conclusions:—Stars of the same class as the sun are equally numerous in all parts of the sky; stars of the Sirian class (blue stars) tend to cluster in much greater numbers in and near the Milky Way than in other parts of the sky.

Variable, and New or Temporary Stars.

One of the most interesting applications of the spectroscope is in the search for the cause of the observed variability of brightness of many of the stars; for it holds out to us some hope of our being

able to fathom some of the mysteries of what we may call the life history of a star.

The study of the spectrum of the variable star Mira Ceti has shown that from time to time there is something of the nature of a conflagration; for when the star is at its brightest the hydrogen lines in its spectrum appear very bright, whilst at the minimum these bright lines disappear. This star emits more than 240 times as much light at one time as at another. The recurrence of the phenomena, which have been known to be going on with very considerable regularity since 1667, seem to point to the possible existence of two or more bodies in the system, one of which disturbs the other.

As a special case of variability, "new stars" present themselves. A new star in the constellation of Auriga was discovered by Anderson of Edinburgh on January 24, 1892, when the star was of the fifth magnitude. The photographic plates of Wolf at Heidelberg and Pickering in America supplemented one another to prove that the outburst of the star was very sudden, probably within twenty-four hours of December 9, 1891. It reached a maximum on December 20, and after slight fluctuations in brightness, it rapidly faded away in April 1892, but in August 1892 it increased in brightness again, and after remaining tolerably constant in brightness for many months, it grew much fainter, but was still visible in 1909.

During the first appearance the spectrum was carefully investigated, and a remarkable feature was the simultaneous appearance of broad bright and dark lines side by side, the dark lines being on the ultra violet side in each case. Hydrogen, helium and sodium were prominently represented by these pairs of lines. The significance of these broad pairs is not yet understood.

In the second appearance the nature of its spectrum indicated that it was a nebula, for it had bright lines in the characteristic positions (see p. 82).

Before the end of the nineteenth century, six other new stars had appeared, most of them close to the Milky Way; in all cases the characteristic pairs of broad and dark lines at first appeared in the spectrum, only to be replaced later on by the mysterious nebular lines.

NEBULÆ AND STAR CLUSTERS.

Probably few of Herschel's discoveries struck the imagination more than that series of observations, in which by the use of increasingly powerful telescopes he was able to "resolve" many of those celestial objects, which to the naked eye or in a small telescope appear as faint patches of light or nebulæ, into groups of separate stars which we now know as clusters. He passed no less than 2500 nebulæ and clusters in review, and having found that his most powerful instruments showed many nebulous patches to consist of stars, whilst in the smaller instruments no such structure could be seen, he was led to believe that all nebulæ would be found to consist of stars if instruments powerful enough could be made. But in 1864, Huggins found that a bright nebula in the constellation Draco gave a spectrum of three bright lines, the brightest being situated in the green, the others close to it in the blue. This remarkable discovery disclosed an apparently essential difference between nebulæ and stars. In the next four years Huggins had examined the spectra of about 70 nebulæ. About two-thirds of these gave a continuous spectrum, the rest gave a spectrum of bright lines, and thus the fact was established that the luminosity of many nebulæ is due in the main to the glowing of incandescent gases. (Frontispiece, line 11.)

Among those bodies which have hitherto been classed together as nebulæ, two different types have been discovered. In one type the spiral form is seen, in the other the form is either irregular or

ring-shaped, or disc-shaped like a planet. Recent spectroscopic observations suggest that the spiral nebulæ have a continuous spectrum, and in some cases the continuous spectrum is interrupted by dark lines. This has suggested the idea that spiral nebulæ are in reality star-clusters, so remote that the stars are not resolvable in our largest telescopes.

Many attempts have been made to identify the bright green line, invariably seen in a nebula which emits any bright lines at all, with some definite gas known on the earth. The present view is that we have not yet found the element with which this line should properly be connected. Keeler's work on the spectra of the gaseous nebulæ has shown that the wavelength of the green nebula line is 5007·05.

It appears that there is not any dark line in the solar spectrum or in any stellar spectrum which can be attributed to the same element.

Comets.

The characteristic feature in the spectrum of a comet is the set of bright bands or flutings distributed at intervals through it, often upon a faint continuous background. These bands are found to be very similar to those seen in the blue part of the flame of a candle, and are attributed to the hydrocarbons. In certain cases, in addition to the hydrocarbon flutings, the presence of carbonic oxide and cyanogen makes itself known by the addition of other characteristic flutings. The head of a comet is in general much brighter than the tail, and these features of the spectrum are most strongly seen near the head; but if the nucleus is examined, a continuous spectrum, very often crossed by bright sodium lines, is generally detected.

Fig. 34 represents three spectra: the first that of the hydrocarbons (or "candle-flame" spectrum seen in the blue lower part of a candle-flame), consisting

of five groups of lines or flutings; the third shows the spectrum of carbon monoxide and hydrocarbons, and the second the spectrum of a comet.

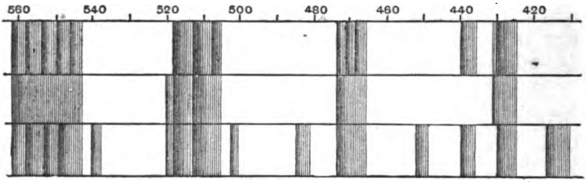


FIG. 34.

The similarity of the spectrum of a comet and the spectrum got by combining the spectrum of hydrocarbons and carbon monoxide will be at once noticed, but the resemblance is not quite complete.

CHAPTER VIII

MEASURING MOTIONS OF RECESSION AND APPROACH

IT is not many years ago that one of the leading astronomers of the day was lamenting that there was no hope of our ever being able to measure the velocity of approach or recession of stars, and that this was a complete bar to advance of knowledge in a certain direction in astronomical matters. The lament was groundless, for in 1868 Dr. Huggins announced his success in utilizing the spectroscope for measuring the velocity with which Sirius and some of the other brightest stars approach the sun, and it is not too much to say that many of the most remarkable advances recently made in astronomical knowledge are the results of the development of his method.

Huggins' method for measuring the radial velocity

of a star consists in observing the spectrum of the star and the spectrum of some terrestrial source of light (as, for instance, an electrical discharge in a tube filled with hydrogen gas) either simultaneously by some optical device or alternately in rapid succession. Attention is confined to corresponding lines in the spectra, and their relative positions are very carefully measured; the position of the bright line in the hydrogen spectrum is compared with that of the corresponding hydrogen line in the star spectrum: and when the adjustment of the instruments is perfect, it is found that there is in general a minute shift of the star line, relative to the terrestrial line.

The position of a line in the spectrum depends on the wavelength of the light which produces the line. If the wavelength were minutely increased the line would move minutely towards the red end of the spectrum; if the wavelength were diminished the line would move towards the violet end of the spectrum. By Huggins' method the hydrogen line in the star spectrum was found in a position which corresponds to a wavelength slightly different from that which the corresponding line in the spectrum of the terrestrial source has; and he ascribed the change in wavelength to the velocity of the star. That the reader may understand why the light forming the hydrogen line should have different wavelengths according as it comes from a star in motion or from a terrestrial source or a star at rest, it is necessary to explain the principle of Doppler, discovered in 1843, upon which Huggins' method is based. It may be stated in rough terms as follows: When any origin of waves of any kind approaches an observer, the waves are shorter than when there is no relative motion. When the origin of waves recedes from an observer, the waves are lengthened.

Thus if a stellar hydrogen line takes up in the spectrum a position which is too near the blue end

for exact coincidence with the corresponding terrestrial hydrogen line, it means that the wavelength of the stellar line is too short and that the star is approaching the earth. The indication of the *direction* of the velocity is definite.

To get ideas as to how the *magnitude* of the velocity is determined we may proceed on the following lines. Let A be the position of a star which is emitting light, and let us confine our attention to light of a definite wavelength λ, and frequency n per second; the light will pass outwards from A equally quickly in all directions, so that the wavefront is a sphere. Let us consider only the directions $A\ O$ and $A\ O'$, and suppose that the light reaches the points O and O' at the end of one second. In that second the stationary star emits n waves each of length λ.

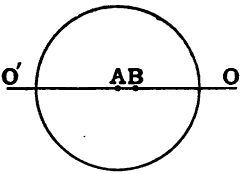


FIG. 35.

Hence $A\ O = A\ O' = n\lambda = 186{,}000$ miles. Now suppose that in that second the star moves with uniform velocity x miles per second from A to B, a point situated on the line $O'\ A\ O$. Then $A\ B = x$ miles. The wave emitted from A at the beginning of the second reaches O and O' at the end of the second, just at the moment when the n^{th} wave, emitted at the end of the second from B, leaves B. Hence the n waves are compressed into the space $B\ O$ in the direction in which the star moves, and are (drawn out) spread over a space $B\ O'$ in the opposite direction. The compressed waves are shorter than they would be if the star had been stationary. The compression is greater the more quickly the star moves, and the change in the wavelength is proportional to the velocity of the star.

The numerical relation is not difficult to find. The wave emitted from A at the beginning of the second

reaches O and O' at the end of the second just at the moment when the n^{th} wave is being emitted by the moving star at B. Hence we have

n *shortened* waves in $B\,O$,
n *lengthened* waves in $B\,O'$,

and had the star been stationary at A, we should have had n *normal* waves in $A\,O$.

The amount of shortening s of each wave is clearly equal to the same fraction of the normal wave λ as $A\,B$ is of $A\,O$. But $A\,B$ is x miles and $A\,O$ is 186,000 miles. Therefore the shortening of the wave is $\frac{x}{186000}$ths of the normal wave. Thus we have

$$\frac{s}{\lambda} = \frac{A\,B}{A\,O} = \frac{x}{186{,}000},$$

and consequently $x = \dfrac{186{,}000}{\lambda} \times s.$

We have spoken of the result of a motion of the star towards the earth, but it is easy to show that an equal motion of the earth towards the star would produce an almost equal effect of the same kind.

Knowing the normal wavelength of hydrogen, and measuring from the spectroscopic observations what change of wavelength was indicated by the displacement of the stellar hydrogen line, Huggins deduced the velocity of the star, x miles a second. The measurement is a peculiarly difficult one, and extraordinary care is required for the detection of the minute shift of the stellar lines. The amount of shift observed in the case of a given star varies according to the time of year on account of the orbital velocity of the earth, or rather that component of it which contributes to the relative velocity of approach or recession of the star and the observer; but astronomers have no difficulty in making allowance for this.

In the memoir in which the success of the attempts to detect the shift is recorded, Huggins states that he had had this object in view more than five years

before the publication (1868) of the results of successful efforts. Thus whilst the success of this pioneer in stellar physics depended, in his first work on the chemistry of stars (page 75), upon the general coincidence between dark lines in the stellar spectrum and bright lines in the spectrum of the terrestrial source, here in his later work his success turned upon his being able to detect minute deviations from coincidence which had at first escaped his observation but which theory indicated must necessarily exist.

The change in the wavelength of light which was first pointed out by Doppler in 1843 as the necessary result of the relative motion of the source of light and an observer is also detected in the case of waves of sound. The apparent change in pitch of the note given by the bell of a bicycle or the bell of a hansom cab may be detected by a delicate ear, the change taking place when the relative velocity of the observer and the bell changes, and being most marked when the relative velocity changes from a motion of approach to a motion of recession. The apparent change of pitch in the note of the whistle of a locomotive was studied in 1845 by Buijs Ballot in his experimental confirmation of Doppler's principle, and again in 1875 by Vogel.

The practical difficulties of applying the method to astronomical problems were so great that Huggins, the observers at Greenwich, Vogel at Potsdam, and Seabroke at Rugby, after doing all that was possible in the refinement of visual observations, laid the work on one side. In 1888 Vogel made a great advance by introducing photographic methods, and after three years' work was able to publish the results of his labours in the shape of a list of the radial velocities of fifty-one of the brighter stars visible at Potsdam.

The work has since been taken up in America by Campbell and by Frost, in Russia by Belopolsky,

in France by Deslandres, in this country by Newall, at the Cape of Good Hope by Gill, and again by Vogel and Hartmann at Potsdam with a much more powerful outfit than that previously used, and by Küstner at Bonn.

In the practical arrangement for using the spectroscope for these determinations, it is customary to attach a spectroscope to the eye-end of a telescope in such a way that the slit is placed in the principal focus of the object-glass of the telescope, and so that the axis of the collimator—*i.e.* the line joining the middle points of the slit and of the collimating lens—coincides with the axis of the telescope. The telescope is then pointed to a star, and the light from the star after passing through the object-glass proceeds in a converging conical pencil of rays towards the focus, and is thus concentrated in the image of the star formed on the slit of the spectroscope. In fact the image of the star which is usually viewed with the eyepiece, is thrown upon the slit. Some of the light passes through the slit, and thence through the spectroscope, forming a spectrum upon a photographic plate placed in the camera. Plate IVA is reproduced from a photographic plate taken with the photographic spectroscope attached to the 25-inch refractor of the Cambridge Observatory, and shows the spectrum of the stationary source of light set side by side with the star spectrum on the same photographic plate. Plate III shows the spectroscope attached to the telescope.

Developments of the spectroscopic method of measuring velocity.

Having succeeded in getting trustworthy results by photographic methods, Vogel examined the spectrum of the variable star Algol, looking for confirmation or refutation of the theory, that the brief diminution in brightness that takes place in that star with such wonderful regularity, is due to a partial

eclipse of the star by a dark companion. He found that shortly before minimum Algol is receding from the sun, and soon after minimum it approaches the sun, the velocity changing from +42 kilometres per second to −42. Thus the eclipse theory is fully confirmed. Eclipses can only take place in such systems when the plane of the orbit of the two bodies is very nearly or completely edge-on to the observer. But several variable stars of the Algol type are known to us, and since we cannot but imagine that it is a matter of chance that their orbits should all be disposed in this particular manner with respect to the earth, we must regard it as probable that there are hundreds of similar systems for which the condition for eclipses is not fulfilled. We may then expect to find many a star whose velocity in the line of light is variable, the variation being due to the fact that the star belongs to a binary system, in which one star revolves round another and so is sometimes approaching the earth and sometimes receding from it.

Vogel himself confirmed this surmise by discovering that the bright star Spica, in the constellation Virgo, has variable velocity and is thus a spectroscopic binary. Between these two discoveries Pickering announced that the bright star Mizar in the tail of the Great Bear has a spectrum in which certain lines are periodically seen double. He explained the appearances by showing that if the star, which in the telescope seems to be a single star, were in reality double, but so remote that the two components could not be seen separate, then the light of the two stars would be thrown into one spectrum by the prismatic camera which he used. If a photograph were taken at a moment when both stars were moving across the line of vision, the two spectra would be superposed in such a way that the similar lines in the two spectra would be coincident and would appear single. If, on the other hand, a photograph were taken when

one star was approaching the earth, and the other star in the system receding from the earth, then the lines in the two spectra would, in virtue of the velocities of the stars, be shifted in opposite directions in the spectrum, and might, if the velocities were large enough, be shifted so far that the lines appeared double wherever there were lines common to the spectra of the two stars. Two years later Pickering announced that β Aurigæ was a double star with a period of about four days. On successive nights the calcium line K appeared alternately single and double (Plate IVB). The changes indicate a circular orbit, and as the shift of the components of the double lines indicates a relative velocity of 240 km. per second Pickering inferred that the orbit described in 4 days would be 13 million km. in diameter.

In Pickering's observations no comparison spectrum of a stationary source could be used, and though the two superposed spectra became each the standard of reference to the other, so that the relative velocities of the two component stars could be found, the velocity of either component with reference to the sun could not be found. Vogel in confirming Pickering's result was able to state that the system of β Aurigæ was as a whole moving with a velocity of -28 km. per sec., *i. e.* towards the sun, and, moreover, that the two components were moving in their orbits with velocities which were very nearly equal. Vogel inferred that the masses of the components were very nearly equal.

By these remarkable discoveries we have a new class of heavenly bodies made accessible to our observation. Herschel showed how continued observations of close pairs of stars would in the course of years disclose an orbital motion of one star round the other. Such double stars take years to complete one revolution, and we know of hundreds of such pairs visible in the telescope. But the spectroscope reveals systems in which two or more components exist

hurrying round one another in a few days, whilst the telescope pointed towards the same objects shows nothing more than what the most skilled observer would unhesitatingly pronounce to be a single star. Astronomers now have to distinguish between telescopic binaries and spectroscopic binaries. In the former, the component stars may be two or three seconds of arc apart and readily seen as two separate stars in the telescope. The shortest known periods in such binaries are 11½ and 5½ years, whilst many binaries are known, *e. g.* Sirius, which take 50 years or more to complete their revolution. The motion of such stars in their orbits is slow, and in fact it has hardly been found possible to measure it with the spectroscope.

The spectroscopic binaries are distinguished by short periods, or rather let us say that in the first attack on this new branch of astromony the examples discovered have been those of strikingly short period. But already the advance has been so rapid that we feel confident that there is no real gap between the two types of bodies. We have a pair, δ Equulei, whose period is 5½ years, and this is visible as a double star in the telescope, and is also accessible to the spectroscope. We have another star, η Pegasi, which the spectroscope pronounces to have a period of 2½ years, but since the lines are only displaced periodically alternately towards the red and towards the blue, instead of being alternately double and single in a definite period, we learn that the pair consists of a bright star and a dark star revolving round a common centre of gravity. It may well be that the dark star is a small faint star, too faint to allow the spectroscope to give any sign of its existence, though quite as bright as the faint companions in many of the telescopic binaries. The telescope has as yet disclosed no visible companion of η Pegasi. But the case of Capella is of great interest in this connection. This star was found by Campbell of the

Lick Observatory to be a spectroscopic binary, and the same discovery was independently made by Newall at the Cambridge Observatory. Both observers arrived at the conclusion that the period was 104 days, and Newall pointed out that it appeared from the composite spectrum that the two components must be about of equal brightness, and that they were describing orbits so large that even taking into account the remoteness of the star, as measured by Elkin, the pair might just be visible as an exceedingly "close double" in a very powerful telescope. The observers at the Greenwich Observatory and elsewhere turned their attention to it, and though the American observers with their powerful instruments were unable to detect signs of doubleness, yet at Greenwich Observatory, with the 28 inch refractor, Lewis, Dyson and Bryant were able to assure themselves that the star was elongated in a definite direction, which slowly changed as the weeks passed by. They were thus able to compute an orbit, and to show that the inclination of the orbit to the line of vision was about 30°.

Campbell, at the Lick Observatory, has determined the velocity in the line of sight of several hundred stars. He had already found in 1901 that of these no less than 32 are binary systems, showing their multiple character by variations in their velocity, and he has expressed the view that probably at least one star out of every six will be found to be multiple, and that our own system, with a *single* central sun accompanied by relatively very small bodies, is not of the prevailing type of stellar systems in the universe. Campbell, combining his observations of the radial velocity of 285 stars, has arrived at the result that the common part of these radial velocities indicates that the sun is moving at the rate of 19 km. per sec., or 13 miles a second, towards a point in the constellation Hercules.

CHAPTER IX

THE SUN'S SURFACE AND SURROUNDINGS

If a spectroscope is pointed direct towards the sun or an electric spark, every point in the slit receives light from every part of the sun's disc, or every part of the spark, and the spectrum seen is that of "integrated" sunlight or integrated spark-light. But if a lens is inserted in front of the slit in the proper position in the incident beam of light, an image of the sun or of a spark can be focussed on the slit of the spectroscope, and each point in the slit then receives the light only from that special part of the sun or the spark whose image falls on the point. For solar researches we obtain this end by attaching a spectroscope to the eye-end of a telescope in such a way that, the eyepiece of the telescope having been removed, the slit of the spectroscope is set in the focal plane of the telescope; thus when the telescope is pointed to any spot on the sun, an image of the spot is thrown in focus on the slit, as indicated in Fig. 36. The relatively dark umbra sends light in at the middle points of the slit, between U and U', and the dusky penumbra above $P U$ and below $P'U'$ sends samples of its light through other parts of the slit, and the bright parts of the disc immediately above and below the spot send samples of their light through the other parts of the slit $S P$ and $P'S'$. The resulting spectrum looks like five spectra of different intensities one above the other—bright spectra at the top and at the bottom, and a faint spectrum in the middle, whilst between the middle and the top there appears a spectrum of medium brightness, and similarly between the middle and the bottom. Here then we are clearly looking simultaneously at the spectra of various parts of a

sunspot and of the bright part of the sun's disc immediately close to it. This was the "image-on-the-slit" method that Lockyer developed in 1866 for special studies, and he applied it with great success both to the study of spectra of vapours in the electric arc (p. 158) and in different parts of the sun.

It was found with respect to sunspots that the spectrum of the dark centre or umbra, and also that of the surrounding penumbra was, broadly speaking, similar to that of the brighter parts of the sun's disc, only greatly enfeebled; the inference is that the darkness of a spot is due in great measure to a

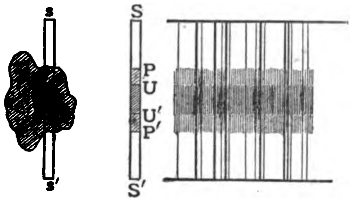


FIG. 36.

general absorption of light. It was also observed that some of the dark lines in the spectrum of the umbra are widened and intensified; the inference is that some vapours are more implicated than others in producing special absorption and thus contributing to the darkening of the sunspot.

Lockyer found further that the hydrogen lines sometimes appear bright over these sunspots or in their neighbourhood, in fact that the state of hydrogen at different points of the sun's surface is not as uniform as we should be led to imagine from the study of the spectrum of integrated sunlight. The constancy observable when the effects of hydrogen all over the sun's disc are summed up or integrated, merely indicates that the average behaviour of hydrogen is constant; and so for other lines, and consequently also for other substances.

The observations of Sidgreaves and Cortie at Stonyhurst have shown that even the integrated effects vary from time to time; for the H and K lines (due to calcium), though generally broad and dark, sometimes show a narrow bright line in the very centre, a result arising doubtless from upheavals of masses of calcium vapour in a state of bright incandescence over considerable regions of the sun's disc.

By the "image-on-the-slit" method it is possible to trace the regions on the sun's disc, where hydrogen or calcium is bright or dark.

The Spectro-heliograph, for photographing the Sun's surface in Monochromatic Light.

We have a splendid instance of the power of this "image-on-the-slit" method in the work of Hale, who has obtained photographs of the whole sun's disc in monochromatic light or, as we may put it, in the light of any one line in the spectrum; he has thus opened out a new field of research in solar physics. After experimenting with smaller apparatus, he has attached to the giant telescope of the Yerkes Observatory a large and powerful instrument, which has been called a spectro-heliograph. It is to all intents and purposes a very large spectroscope with a narrow slit eight inches long; on this slit, an image of the sun's disc is thrown; the image thrown by the large telescope is seven inches across. The actual slit is thus illuminated by a narrow chord of the sun's disc, and we get in the focal plane of the spectroscope the spectra of every point on this chord. Let us now confine our attention to the K line in the spectrum. Hale places a second slit properly arranged in a thin opaque screen in the focal plane of the camera of the spectroscope, in such a position that it will allow only the light of the K line to pass through it, and immediately behind the screen a large photographic

plate, eight inches by ten, is set. Then if there are irregularities in brightness on the sun along the chord of the sun's disc that illuminates the first slit, they will be indicated by irregularities in the brightness of the K line that falls on the second slit. Hale finds that in fact the middle of the width of the K line is bright in some parts of the disc and relatively dark in others. And hence an image of the slit and therefore of the chord of the sun's disc is imprinted on the photographic plate, bright in some parts, dark in others. We see that if the image of the sun were moved slightly, say through one inch, so that a new chord falls upon the first slit, the second slit would receive the K line as before, but the irregularities in the brightness would now correspond to those on the new chord of the sun's disc. If then the photographic plate be moved sideways across the second slit through just the same distance as the sun's image was moved across the first slit, namely, one inch, it will receive the image of the second chord in the appropriate place, namely, parallel to the first chord and one inch away from it. Hale has arranged small electric motors to move the telescope in such a way as to make the sun's image drift slowly and uniformly across the first slit, and simultaneously to move the photographic plate slowly and uniformly across the second slit. Thus as successive parallel chords of the sun's disc fall on the first slit, their images are impressed in the appropriate parallel positions and with their appropriate lengths on the moving photographic plate. In about three minutes all the successive images have been laid side by side, and the developed photograph shows a complete round image of the sun taken in monochromatic light; when the K line is used, the monochromatic light is that emitted by glowing calcium vapour.

Hale's spectro-heliograph can thus give the image of the sun's disc in the monochromatic light of any line that can be made to fall upon the second slit.

Plate V illustrates the results. It is reduced in size from pictures taken in 1906 and 1908. We see in it (i) how bright the glowing calcium vapour is round the sunspots ; (ii) how the zones of latitude in which the sunspots appear are obviously marked out by the brightness of calcium clouds ; (iii) how the mottled appearance extends over the whole face of the sun, showing that there are probably great upheavals of calcium clouds separated by comparatively dark spaces where the less luminous vapour rests between.

A new and special solar observatory has been built on the summit of Mount Wilson in Southern California, and Hale is now carrying on the work there with splendid success. He is now able to photograph the disc "in various lines," and so hopes (i) to study in spectroscopic detail the distribution of the different vapours over the whole face of the sun, as it slowly turns round in the period of about twenty-six days, and (ii) to continue these studies through the cycle of eleven years, and so to trace the changes that may go on as the sunspots and the allied phenomena pass from maximum to minimum and to maximum again.

In addition to Hale's discussion of the material now gathered by him in America, the subject is being worked out by Deslandres at Paris, Kempf at Potsdam, and by Lockyer at South Kensington. The Indian Government also, recognizing the power of this mode of research as well as the opportunities afforded by a solar observatory in India for solving the question of the existence of possible relations between solar phenomena and recurrence of dearth and famine, have had another installation set up at Kodaikanal, at an observatory 7500 feet above sea level, in the Palni Hills, latitude 10° 14′ North, under the charge of Michie Smith and Evershed.

The Sun's surroundings.

In a total eclipse of the sun, the moon passes between the sun and the earth ; and it is the solid

body of the moon which intercepts the light of the sun. The round shadow of the moon falls at a certain time upon the surface of the earth, and it may be as much as 160 miles across. Astronomers calculate when and where the shadow will strike the surface of the earth, and along what line it will move; and observers travel out and station themselves at suitable points on this line to see the eclipse under the most favourable circumstances. The sun's light is cut off by the moon from a small region of the earth's surface, and also from the earth's atmosphere in the same neighbourhood; the sky therefore appears dark, and not only can stars be seen as at night, but a wonderful radiance becomes visible near the eclipsed sun, stretching far away from the sun in all directions. Close to the edge or limb of the sun brilliant protuberances or flame-like projections may be seen, sometimes silvery white, sometimes yellow or pink, sometimes crimson. The moon passes slowly in front of the sun during the total eclipse, and presently a narrow crescent-shaped strip of his surface becomes exposed, and the light of this strip lights up the earth's atmosphere; the faint far-reaching streamers become more and more difficult to see as the crescent increases, and long before half the surface of the sun's disc is exposed, all sign of the true surroundings of the sun are obliterated from view, by the brightly illuminated haze in the earth's atmosphere.

The general radiance which is seen in total eclipses extending to considerable distances from the sun is known as the "corona," and the streamers have been seen extending as much as six or eight diameters of the sun from his limb. As the diameter of the sun is 866,500 miles, it is clear that the corona extends over many millions of miles. The flame-like projections seen close to the sun's limb are called "prominences," and the lower or interior part of the sun's atmosphere in which these coloured flames arise

is known as the "chromosphere," whilst the name "photosphere" is given to the bright surface of the sun itself. No sharp line of demarcation can be traced between chromosphere and corona. But the spectroscope shows that the light coming from the two regions is very differently constituted.

Plate VIA reproduced from a photograph taken by Professor Barnard during the eclipse observed in North Carolina in 1900, shows something of the kind of structure seen in the surroundings of the sun, though it fails to convey anything of the extraordinarily impressive beauty of the pearly colouring of the radiance of the "corona."

Spectrum of the Corona.

The spectrum of the corona consists of (i) a few bright lines, one of the brightest being in the green part of the spectrum, and being known as the green corona line; (ii) a tolerably bright continuous spectrum, and possibly (iii) some dark absorption lines which appear to be similar to those seen in the ordinary solar spectrum. It appears therefore probable that the corona emits light of its own, due to the glowing of some gas which on account of its extension and distance from the sun's surface must be in a state of the most extreme tenuity. No gas that we have knowledge of on earth gives a spectrum containing the lines seen in the corona; but so certain do astronomers feel of the indications of the spectroscope that they have given the name "coronium" to the substance which emits the lines seen in the spectrum of the corona. The dark absorption lines, if present, may be due to the reflexion of sunlight by dust floating in the corona. The continuous spectrum is possibly due to incandescent dust, or possibly to the phosphorescence of rarified gases in the neighbourhood of the sun; but much more investigation is needed before it will be possible to speak with certainty on these points. It would seem from several

observations in India in 1898 and in Sumatra in 1901, that the bright rays that form such a remarkable feature in the corona, especially near the poles of the sun, are not due to the brightness of glowing "coronium." Whatever they may be due to, it is clear that the matter of which they are composed must be in an excessively rarified condition. Comets speed through these regions near the sun, and little or no disturbance in their orbits can be detected.

The Spectrum of Solar Prominences and of the Chromosphere.

De la Rue's photographs of the solar eclipse observed in Spain in 1860, proved conclusively that the prominences belong to the sun; for they showed that the dark body of the moon gradually eclipsed the prominences just as it eclipsed the sun's edge. Knowledge accumulates slowly, when the opportunities of studying the phenomena are limited to a few minutes in as many years. It was in 1868 that the spectroscope was first applied to the investigation of the prominences, and at once the observations of Janssen, J. Herschel, Tennant and Rayet revealed the fact that they emit spectra like those of glowing gases; in particular, bright lines were seen which proved that they were in large part produced by glowing hydrogen, and that other glowing vapours were present.

Between the years 1867 and 1869, however, the rate of the progress of our knowledge about the immediate surroundings of the sun was suddenly increased by the discovery of a method which made it possible to see prominences and chromosphere in full sunlight. It was realized that the brightness of a prominence does not depend on the occurrence of an eclipse. When a telescope, armed with a spectroscope, is pointed in full sunshine towards a prominence, the effects seen are the superposition of the bright-line spectrum of the prominences upon the spectrum due

to the sunlight reflected and diffused by the haze and dust in our atmosphere. Now if the power of the spectroscope is increased, the light entering the slit from the sky, and containing as it does, light of all wavelengths, is spread out in a long spectrum; whilst on the other hand, light entering the slit from the prominence, and containing as it does light of only a few special wavelengths, is not spread out, but remains concentrated in its bright lines, which are only more widely separated in consequence of the higher power. The increase in power of the spectroscope diminishes the brightness of the sky spectrum and leaves the brightness of the prominence lines very slightly altered.

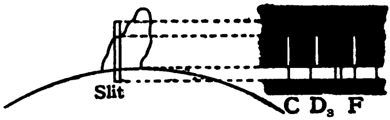


FIG. 37.

If an image of the sun is thrown upon the slit in such a way that the limb of the sun falls on the middle of the slit and that the slit is radial to the sun's image, as indicated in the figure, then it is possible so to arrange the observations that the bright lines of the prominences may be seen projecting as it were beyond the spectrum of the sun itself and appearing upon a comparatively faint spectrum of the light diffused by the sky (Fig. 37). This idea had occurred to Lockyer and to Zöllner and to Janssen independently; they all realized the necessary conditions and saw the bright lines in this way without an eclipse. At first Lockyer and Janssen had used only narrow slits; they only saw narrow strips of the prominence whose image was thrown on the slit, but by combining a series of observations it was possible to construct a picture of the whole

prominence. Huggins used a piece of ruby glass and a wide slit, and was thus enabled to see the whole outline of a prominence at once. Lockyer and Zöllner took the final step in pointing out that a wide slit used in conjunction with a spectroscope of sufficiently high dispersing power would show prominences to the best advantage. In this way have prominences been observed ever since.

The prominences were seen to have the appearance of huge flames or clouds, apparently floating above what we should call the surface of the sun, with the most varied forms; some of them extended but a few hundred miles, others rushed up to a height of thirty or forty thousand miles, and even in exceptional cases to heights of several hundred thousand miles. (The diameter of the sun is 866,500 miles.) Some were like straight pillars of flame, others like whirling vortices; some like banks of brilliant incandescent cloud, others like flames rushing outwards as if under the influence of some stupendous eruptive forces, and yet others sinking back again towards the sun's surface.

To give an idea of these prominences we cannot do better than reproduce (Plate VIb) part of the photograph secured by Barnard during the eclipse of 1900. The spectroscope shows forms as remarkable as these, without any eclipse.

Here and there, only the indications of hydrogen are found in the spectra of these bright flames; again, in other places or at other times helium takes part in the outbursts; now and then metallic lines are visible. Lockyer has described a cloud of incandescent magnesium which he saw floating high up above a prominence, and recognized as magnesium from the position of the bright line in the spectrum. Calcium is prominent in some of the most remarkable prominences ever recorded, if we are right in attributing the lines H and K to calcium.

Young, who has made special study of the chromo-

sphere, has classified prominences in two groups, *quiescent* and *eruptive*. These are distinguishable alike by their form and by their spectra; for the quiescent prominence generally shows only hydrogen lines in its spectrum, whilst the spectrum of eruptive prominences is marked by the presence of bright lines due to metals.

It will be remembered that one and the same prominence may be studied in the spectroseope in the light and colour of any line in the spectrum that is bright. Thus a hydrogen prominence will appear red if viewed in the light of the C line (H_α) of hydrogen; it will appear green-blue, if viewed in the light of the F line (H_β) of hydrogen. If glowing magnesium is present in the prominence, we may see the form of the magnesium cloud by looking in the light of one of the magnesium lines, for instance *b* in the green part of the spectrum; we might thus be tempted to speak of a green cloud of magnesium, but we must bear in mind that the colour attributed to the cloud is due to our having viewed it in the green part of the spectrum; it may however arise that we are satisfied that the sum total of the effect of all the magnesium lines results in a green light. In the case of some hydrogen prominences seen during a total eclipse, the colour as seen by a telescope without any analysis of the light, is pink or even crimson.

We have made casual reference to helium as a recognized element, but in the early days of the study of solar physics between 1870 and 1875 the origin of the bright yellow line, often seen in prominences so close to the sodium lines D_1 and D_2, that it was called D_3, was a matter of great difficulty. No element was known to emit a line corresponding with D_3. The line appeared in the prominences under conditions so similar to those in which the hydrogen lines occurred, that it seemed clear that D_3 was a hydrogen line; but soon Lockyer, by very careful observation, found prominences which showed hydrogen to be

rushing violently in one direction in a prominence, as indicated by corresponding displacements of *all* the hydrogen lines, whilst the D_3 line was displaced in an opposite direction, indicating that the substance that emitted the D_3 line was moving in the opposite direction. (It may well happen that in looking at prominences on the edge of the sun we look through a hydrogen prominence and see a helium prominence far behind.) Hence Lockyer and Frankland coined the name helium for the element, and for more than twenty years the origin of the line remained a mystery, till Ramsay discovered in 1895 that it was due to the gas derivable from the mineral cleveite.

In 1870, during the eclipse of December 22, Young was observing the spectrum of the edge of the sun, as the moon's dark outline gradually covered over the small remaining crescent of the sun's disc. Just as the crescent vanished, the dark lines in the spectrum seemed to be suddenly replaced by bright lines. Stone saw the phenomenon in a total eclipse of the sun in 1874 in Africa, but though Lockyer and Fowler got evidence in the photographs taken in Africa in 1893 of the existence of many bright lines, not until 1896 was the whole wonder of the appearance realized. The "flash" was of such short duration that no eye observations could suffice to record what occurred except in quite general terms, "that all the dark lines became bright." Shackleton secured a photograph of the phenomenon during the eclipse which he observed in Novaya Zembla in 1896, and since that year many and various have been the successes in getting photographic records.

The prismatic camera (page 74) without slit or collimator deals with the narrow curved crescent of the nearly eclipsed sun as if it were a narrow slit, and the resulting photograph shows a multitude of images of the crescent set side by side; each image corresponds to a bright line in the spectrum. Thus if there are 20 hydrogen lines in the range of

spectrum photographed, there will be 20 images of the crescent each portrayed in the light of hydrogen. If there are 50 bright iron lines, we shall get 50 more images of the crescent each set in its appropriate place in the spectrum.

Plate VII is taken from a photograph obtained by Lockyer and Fowler in 1898 and shows how the phenomena change as the crescent becomes narrower and narrower. At first the light of the unhidden photosphere, still visible on the inner edge of the crescent, preponderates, and we see the dark lines with here and there a bright line interspersed. Then the photospheric light is hidden by the advancing moon, and we see all the crescents due to the bright incandescent vapours that lie on the surface of the sun, and are thus seen in profile at the edge in the almost eclipsed crescent. Finally the dark moon covers even those vapours which float higher up in the innermost surroundings of the sun. From the lengths of the crescents we can in many cases get an indication of the height of the layer from which the crescents emanate. Thus the hydrogen crescents are notably longer than any others except perhaps those of calcium, indicating that glowing hydrogen floats above the metallic vapours.

Plate VIII is taken from a plate that illustrates Hills' preliminary report on the eclipse of 1898, and shows the similarity of the "flash" spectrum at the beginning and end of totality, and also the similarities and divergencies between the relative intensities of the bright lines in the "flash" spectrum and the dark lines in the ordinary solar spectrum. It is a remarkable fact that the flash spectrum more closely resembles the reversal of the spectrum of certain stars like γ Cygni and α Persei than that of the solar spectrum.

We see as the result of some of the preliminary studies of the phenomena, that closely surrounding the photosphere there is a layer of mixed incandescent vapours, which we must regard as forming the lower

part of the chromosphere. This layer may exert considerable absorptive power, because its spectrum shows that it is full of vapours giving out vibrations of definite period, and such vapours can absorb vibrations of like period. It is inferred that photospheric light in passing through this layer is robbed of many of the components of the light which it originally emits; the layer is accordingly often referred to as the "reversing layer," and is regarded as giving rise to the Fraunhofer lines in the solar spectrum.

The spectrum which we call the solar spectrum is thus the result of most complex phenomena. We imagine it to be the final result of the analysis of light which originally emanates from the incandescent photosphere and reaches us after passing (i) through certainly more than five or six hundred miles of incandescent vapours which themselves emit the light we analyze in the "flash" spectrum, and which have been regarded as the "reversing layer," (ii) then through several thousands of miles of chromosphere in which vapour of hydrogen and calcium is shown to be present in the forms of prominences, (iii) then though several hundreds of thousands of miles of faintly luminous corona, and (iv) through nearly ninety million miles of space between us and the sun, and finally through the earth's atmosphere.

CHAPTER X

MOTIONS ON THE SUN—ROTATION OF THE SUN AND PLANETS

THE spectroscopic method of measuring the velocity of approach or recession of stars is applicable in the

most general sense to the measurement of any velocity in the line of sight, provided the velocity is larger than about 1 kilometre per second, this being at present the smallest that is with certainty detectible by the spectroscopic method. Velocity of approach is indicated by the displacement or shift of a line from its normal position in the spectrum towards the violet: velocity of recession is shown by the shift of the line towards the red.

Some remarkable results have been obtained from the spectroscopic examination of the vapours on the sun. When an image of a prominence on the limb of the sun is thrown upon the narrow slit of a spectroscope, it is seldom found that the bright line due to

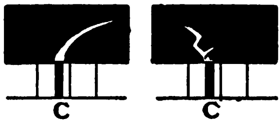


FIG. 38.

the prominence is exactly in coincidence with the corresponding dark line due to the same element within the edge of the sun's disc. The shift indicates that the vapour producing the prominence is in violent motion.

In this way the early observers, Lockyer, Young, Vogel, Zöllner and Janssen, detected enormous velocities not only near the edge of the sun, but also on the disc itself. The appearances in the spectroscope are sometimes very remarkable. The bright line instead of looking straight may seem bent and distorted. Sometimes the distortion consists of a twist of the bright line towards the ultra red, indicating that the prominence is rushing rapidly from the observer (Fig. 38). Sometimes the line is broken, the lower part being bent one way and the upper part in the opposite direction (Fig. 38). It should

be noted that when such velocities are observed near the edge (or, as astronomers call it, the "limb") of the sun's disc, it means that the matter involved in motion is rushing along the surface of the sun; and that when the velocities are observed near the centre of the sun's disc, it implies that the matter involved in motion is either rising violently upwards or rushing downwards along a radius of the sun; or, to be more precise, in all cases the spectroscope gives us indications only of that component of the velocity of the moving matter which is in the line of sight.

By their studies also of the changes in *form* of the prominences, as seen in the monochromatic images with wide slits, the early observers were led to interpret the swiftness with which a prominence might be seen to change its shape as indicating velocities of matter rushing outwards or inwards along a radius of the sun. Young, in his book *The Sun*, describes eruptions of prominences, which from a seemingly quiescent state at one moment of observation "had been literally blown to shreds by some inconceivable up-rush from beneath" as judged by observation made half-an-hour later. "When first I looked [after an interruption in the observations] some of them had already reached a height of nearly 100,000 miles, and while I watched them they rose with a motion almost perceptible to the eye until in ten minutes the uppermost were more than 200,000 miles above the solar surface. This was ascertained by careful measurement." Here then is evidence, from actual observation, of movements of a velocity of the order of 200 miles per second.

The spectroscope is used in two distinct ways in solar work, either with a wide slit to give monochromatic images of a bright prominence (page 102), or with a narrow slit to give information about the position of the lines in the spectrum. When we see a whole prominence change its form, as we look at its monochromatic image (with a wide slit), the change of

form may be interpreted as we would interpret any other telescopic observation; we should, however, lay more weight on observations of motion *along* the slit than on those *across* it. On the other hand, when the spectrum of a prominence is observed in a spectroscope with narrow slit, then, if the bright lines are seen to change their position along the spectrum, we have evidence that at different moments we are looking at different parts of a prominence which have different velocities in the line of sight. It is thus clear that the spectroscopic (narrow slit) observations cannot be used to corroborate the evidence of monochromatic (wide slit) telescopic observations on one and the same object. The average and maximum velocities detected by the spectroscope agree in magnitude with the average and maximum velocities detected by telescopic observations. Hence we are justified in taking the spectroscopic evidence as supplementing the telescopic evidence.

Rotation of the Sun.

It was known to very early observers that the sun was at certain times marked by dark sunspots, and Galileo, early in the seventeenth century, satisfied himself that they slowly traversed the disc along definite curved or straight lines, in such a way that the rotation of the whole sun about a definite axis was indicated. Continued and careful telescopic observations both of sunspots and of the small bright markings which were called faculæ proved that the sun does not rotate like a solid body, for the markings near the sun's equator move more quickly than those in high solar latitudes or near the poles, so that three spots in different latitudes, but on the same line of solar longitude in one rotation, are not on the same line in the next.

When the spectroscopic method of determining velocity in the line of sight was established, it was seen that it afforded a quite independent mode of in-

vestigating the law of rotation in different latitudes. For if on the slit of a very powerful spectroscope an image of the sun's disc were thrown in such a way that the slit was illuminated by light from the edge of the sun's disc, then the velocity of approach or recession of that edge of the sun could be deduced from measurements of the minute displacement of the solar lines in the spectrum. The displacement is that due to a velocity of about 1·2 miles per second, and only amounts to a quantity equivalent to $\frac{1}{180}$th of the interval between the yellow lines of sodium. But nevertheless Vogel succeeded in detecting it in 1871 and the Greenwich observers also measured it. It is true that even apart from the minuteness of the quantity to be measured the observations had to be taken with great care and in large numbers in order to eliminate the effects of the local disturbances such as are seen in prominences (p. 109); but Dunér succeeded in making a fine set of observations of the velocity of different points on the edge of the sun's disc extending on both east and west limbs from solar latitudes 75° south to 75° north. Adams has continued and extended the work quite recently in California.

A comparison of the periods of rotation derived from three methods of observation gives the following results, which have been put in the form of a table by Miss Clerke in her book *Problems in Astrophysics*:—

Heliographic Latitude.	*Periods in Days.* Faculæ.	Sunspots.	Reversing Layer.
0°	24·66	25·09	25·46
15°	25·26	25·44	27·49
18°	25·48	25·81	31·83

The results of the spectroscopic method are entered in the last column under the heading "reversing layer"; for they have been obtained from the spectroscopic study of the dark lines which have their origin in the reversing layer. Whether these numbers need correction, or if not, how they shall receive ex-

planation, is a matter that only further and still more careful and accurate observation can decide.

Rotation of the Planets.

The diameter of the sun is about 866,500 miles in length, and a spot on the equator travels over 2,723,000 miles in 25 days, giving an equatorial velocity of 1·2 miles per second. The planet Jupiter, on the other hand, is 88,200 miles in diameter and completes a single rotation in about 9 hours and 55 minutes, there being variations in the period deduced according to the position and nature of the spot observed, for there are curious differences (in many ways comparable with those deduced from careful studies of the movements of sunspots) in the movements of different parts of Jupiter's disc. The period given, however, is near enough for our present purpose, which is to point out that a spot on the equator of Jupiter moves with a velocity of about 7½ miles a second.

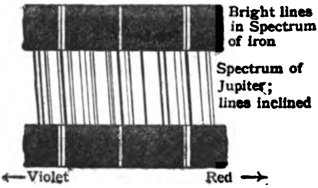


FIG. 39.

The Greenwich observers in 1876 had been able to measure the period of rotation of Jupiter by spectroscopic methods exactly analogous to those adopted for the sun. Deslandres in 1895 revived the observations and showed that if the image of Jupiter is thrown on the slit of a spectroscope, with the equatorial diameter of the planet on the slit, and if then the spectrum of the planet is photographed, it can be seen that the lines in the spectrum are inclined in a curious way in consequence of the rotation of the planet. Consider such a spectrum as being laid before us in such a way that the length of the spectrum is horizontal, and that the bottom of the

spectrum is formed by light coming from the receding edge of Jupiter's disc. The lines at the top of the spectrum are shifted towards the violet, and those at the bottom are shifted towards the red; those midway between the bottom and the top will not be shifted, since they are due to light coming from the centre of Jupiter's disc, which in its rotation moves only across the line of sight and not along it. The lines in the broad spectrum then show a slight tilt or inclination with respect to the vertical position that they would have if the spectrum had been that of the sky, as is indicated in Fig. 39.

In consequence of the fact that Jupiter shines not by his own light but by reflected sunlight, the inclination of the lines is nearly doubled. And it is not difficult for the astronomer to calculate from the measured inclination of the lines and the scale of the spectrum what is the period of Jupiter's rotation.

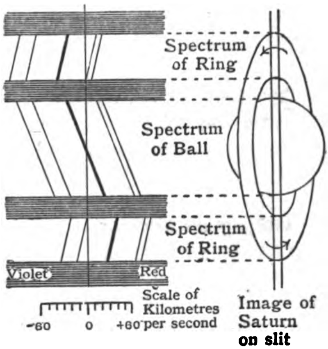


FIG. 40.

The yet unsolved mystery of the period of rotation of the planet Venus has been attacked by Belopolsky and other observers in the spectroscopic method, but hitherto the results are avowedly ambiguous.

Results of the greatest importance with regard to the theory of Saturn's rings were derived by Keeler. For by applying the spectroscopic method to the determination of the period of rotation of the ball and rings of Saturn (Fig. 40), he conclusively showed—and his result is confirmed by Campbell, Vogel and others—that the rings rotate in such a manner that the inner

parts move more quickly than the outer parts, and must be thus regarded as being made up of a number of discrete bodies. Keeler thus achieved the observational proof of the correctness of the theoretical views expounded by Clerk Maxwell, namely, that the only possible way of explaining the stability of the system of Saturn's rings on the basis of any properties of matter known to us on earth is to admit that it is made up of separate small bodies of the nature of meteorites, and is not either a liquid or rigid solid system.

CHAPTER XI

ABSORPTION LINES DUE TO THE EARTH'S ATMOSPHERE—SPECTRA OF THE MOON AND PLANETS

THE appearance of the sun is very different according as the sun is high in the heavens, or low down. A study of the spectrum under different conditions shows that certain dark lines are always present, but that when the sun is near the horizon, not only is the blue end of the spectrum in general considerably enfeebled relatively to the red end, but also new dark lines and groups of lines make their appearance in the red, the yellow and the green.

The red colour of the sun near the horizon is in fact due to the suppression of various components of the sun's light as it travels through great tracts of the earth's atmosphere, and these tracts are naturally much greater when the sun is low down in the sky than when it is high overhead.

Brewster and Gladstone in 1860 examined and mapped the groups of lines which appeared in the spectrum of the low sun.

Janssen by observing the absorption due to aqueous vapour proved that many of the groups of

lines were due to moisture in the air. First of all, in 1864 he observed the spectrum of a bonfire on the shore of Lake Geneva, and found that observations made close to the fire merely disclosed a continuous spectrum; on the other hand, observations of the fire from a distance of ·13 miles across the surface of the lake, and consequently through a long column of air saturated with moisture, showed that the spectrum was pervaded by numbers of dark absorption lines. In order to banish the last remaining cause for doubt, he then used a tube over 100 feet long, and having closed the ends by means of plate glass and having provided side valves at the extremities of the tube, he drove the air out of the tube by forcing steam in at a valve at one end and out of a valve at the other end. Then setting up a bright light at one end, he observed its spectrum through the length of the tube, and found that under these circumstances it was marked by groups of lines identical in position with some of the groups of lines in the spectrum of the sun near the horizon. Such lines are shown by these and other experiments to be of earthly origin and are accordingly called *telluric* lines.

Janssen had shown that the appearance of dark bands was due to closely crowded groups of fine lines many of them caused by aqueous vapour. Egoroff showed that two very strong groups of lines in the red, denoted by the letters A and B, and marked by a peculiar and orderly structure, are due to oxygen, an observation which Janssen has confirmed by direct experiments with long tubes filled with oxygen. Janssen has seen these groups of lines in the solar spectrum as observed from the top of the Faulhorn 9000 feet above the sea, and also from the observatory on the summit of Mont Blanc; they are extremely feebly seen, but are visible even under these conditions.

In 1886 Cornu devised a beautiful method of discriminating between the lines of telluric origin and true solar lines. We have seen how the rotation of

the sun can be deduced from spectroscopic observations, by measurement of the displacement of the lines in the spectrum according as the light analyzed is taken from one end or the other of the sun's equatorial diameter (page 111). Only lines of truly solar origin will exhibit such displacement. Accordingly Cornu arranged a powerful spectroscope so that an image of the sun was thrown on the slit, and he mounted the image-forming lens so that it could be steadily rocked from side to side through a small range of such an amount that in one extreme position of the lens the east end of the sun's equatorial diameter fell on the slit, and in the other extreme position the west end of the diameter.

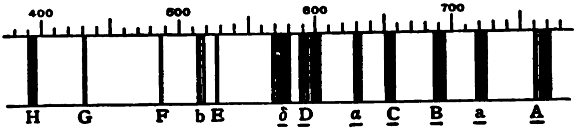


FIG. 41.

Thus the slit was alternately illuminated by light from opposite ends of the sun's diameter, and the true solar lines were seen to oscillate from side to side through small displacements due to the velocity in the line of sight, whilst the telluric lines remained stationary. The stationary lines were carefully measured, and we thus have a list of more than 450 lines in a comparatively short range of spectrum.

In Fig. 41 the absorption bands due to the earth's atmosphere are underlined. The lines *D* and *C* are solar.

Ångström and others have shown that far in the ultra red at wavelength 35,000 there is a strong absorption band due to carbon dioxide.

The Spectrum of the Aurora Borealis.

At times, more especially during that part of the eleven-year period of solar phenomena when the sun-

spots are at a maximum, the sky at night is seen to be bright with "northern streamers" or aurora borealis. From many observations it is certain that this luminosity is connected with the earth's atmosphere. The spectroscope has shown that the spectrum exhibits bright lines on a faintly continuous background, the most easily seen line being that in the green at wavelength, 5571 tenthmetres; other lines are seen at 6298, 5234, 5190, 5005, 4605–4630.

It seems certain that these lines must originate in some gaseous element in our atmosphere; and yet strangely enough there has been the greatest difficulty in tracing it. When Rayleigh and Ramsay discovered argon, the expectation was that the aurora lines would be traced to that element, but no comparable line appears in the argon spectrum. Again, when Ramsay found three more gases—neon, krypton, and xenon—in the air, hopes were again raised. Baly has in fact found in the spectrum of krypton a green line with wavelength 5570·50, which is possibly the green aurora line.

The Spectrum of the Sky by Day.

The sky during daylight, the moon, and the planets all owe their brightness to light emanating from the sun, and the spectroscope shows that in each case the common origin is proved by the existence of the dark Fraunhofer lines arranged exactly as we see them in the spectrum of the sun. There are, however, superimposed differences which we now proceed to describe.

The Spectrum of the Moon.

Spectroscopic observations fully confirm the result arrived at by a variety of astronomical observations, namely, that the moon has no atmosphere. When moonlight is analyzed, it is found that the spectrum does not differ at all from that of the sun; the light of the moon comes from the sun and is reflected to

us through our atmosphere. It shows in its spectrum only such bands of absorption as we know to be of telluric origin.

In consequence of the absence of any absorptive effects attributable to the moon, it has been found of the greatest help in the study of the spectra of the planets to make comparisons between the spectra of the moon and the various planets. If observations are made when the planet and the moon are as nearly as may be equally remote from the zenith, the effect of the earth's atmosphere may thus be allowed for; and an increased darkening of any line or group of lines in the planet's spectrum may rightly be attributed to special absorption in the planet.

The Spectra of the Planets.

Mercury shows little or no special absorption in its spectrum, and we thus have no reason to think that it possesses an atmosphere, or that any atmosphere it may have differs at all from our own. But the crucial observations are difficult, and have not been made from high altitudes in daylight. Ordinarily the planet is only observed near the horizon in twilight.

Venus is the brightest of the planets, and can be seen with the naked eye in full daylight. As her spectrum can be seen simultaneously with that of the sky, direct comparisons have been made, and it appears that her atmosphere exerts absorption similar to our own. Astronomers regard the planet as covered by clouds, which brightly reflect the sunlight and prevent the penetration of the light into the depths of any atmosphere she may have.

Mars' ruddy appearance would lead us to expect definite signs in the spectrum. Huggins and Vogel and the earlier observers agreed in thinking that there was very definite absorption in groups coincident with telluric groups, and concluded that the atmosphere of Mars was like our own. But

more recently Campbell, observing from the altitude of the Lick Observatory and Mount Whitney, has hardly been able to detect more absorption in the case of Mars than in that of the moon.

Jupiter's spectrum is marked by several bands similar to those in the spectrum of the earth's atmosphere, and notably by a band in the red, of unknown origin. From the telescopic appearances of his surface and of changes thereon, astronomers have been led to believe that there is more likelihood of self-luminosity in the case of Jupiter than any of the inner planets; but the spectroscope has not been able to show evidence of it.

Saturn was described by Huggins as having a spectrum similar to that of Jupiter; Vogel saw the band in the red in the same part of the spectrum as in Jupiter, but failed to find it in the spectrum of the rings, an observation which Keeler was able to verify in his investigations (page 113).

Uranus and Neptune are both so faint that observations are very difficult, but observers all agree in describing the absorption bands as far more marked than in any of the other planets. The red band noticed in the spectra of Jupiter and Saturn is more marked still in the two outer planets, and the absorption bands generally preponderate so much that it seems doubtful if the ordinary Fraunhofer lines of the solar spectrum have been distinctly seen. Slipher has recently photographed the spectra of the planets at the Lowell Observatory.

CHAPTER XII

LAW IN THE SPECTRUM—DISTRIBUTION (ACCORDING TO WAVELENGTH) OF ENERGY OF RADIATION IN THE CONTINUOUS SPECTRUM OF A SOLID BODY AT VARIOUS TEMPERATURES

CONSIDER what happens when a spectroscope is pointed at a wire or at a carbon filament which can

be gradually heated by some means, whether by a flame properly arranged or by an electric current whose strength can be increased under the control of the observer, so that the wire can be maintained at any desired degree of incandescence. At first no light passes into the visible spectrum, until the wire is heated enough to glow with a dull red light; and then only red light appears in the spectrum; this red light does not appear as lines or bands, but forms a bit of "continuous" spectrum in the red region only. As the brightness of the glowing wire increases, the spectrum changes in two ways: firstly, the brightness of each part of the visible spectrum increases; and secondly, whereas the light in the spectrum is confined to the red end, by degrees it extends more and more towards the violet end, as the temperature rises. Thus the colours are:

first at dull red heat:	red (faint): no other colours
next at red heat:	red (brighter), orange (faint)
then at bright red heat:	red (still brighter), orange (bright), yellow (faint)
at brighter red heat:	red (much brighter), orange (brighter), yellow (brighter), and green (faint)

and so on, till at the highest temperatures we have finally at white heat: red, orange, yellow, green, blue, indigo, violet. Throughout the observations the spectrum is continuous (not lines or bands), and when the wire is white hot, the spectrum exhibits all the colours that go to make up white light. We thus see that the terms "red hot" and "white hot" have very definite significations.

This summarizes in a rough way the real phenomena of the radiation of an incandescent solid body. In truth, the eye with its idiosyncrasies in sensitiveness (p. 47) *sees* the colours rather differently; for as the temperature of the wire is gradually raised until it glows, the eye first becomes conscious of a greyish glimmer of light in the part of the spectrum appropriate to the green, and then the grey tinge becomes

more definitely coloured; it is certain, however, from other experiments that red light is emitted in larger quantities than the green, though the eye does not see it. Through the sensitive skin on the face or the hand we become aware of the radiation of heat long before the wire is visible to the eye as red hot. In a thorough investigation of the phenomena we have to make use of special means of detecting and measuring radiation independently of skin and eye.

Instruments for detecting and measuring radiation.

In 1821 Seebeck discovered that if two wires of different metals are joined together so as to form a ring or circuit, and if one of the two junctions of the dissimilar metals is heated, then an electric current circulates round the circuit. He found that (i) antimony and bismuth give this "thermo-electric" effect in greater degree than any other pair or couple of metals; and (ii) the greater the difference of temperature of the junctions the greater the electric current produced. Thus if a galvanometer is included in the circuit to measure the current, its indications serve as measures of the difference of temperature at the junctions of the thermo-electric couple. Nobili utilized this discovery in inventing the thermopile in 1834. He argued that when radiation falls upon one junction of a thermo-electric couple its temperature will be raised, if the radiation is absorbed. Accordingly he arranged thermo-electric couples of antimony and bismuth in the most advantageous way for showing the electrical effect; he blackened the junctions with lampblack, so that the incident radiation should be readily absorbed; he connected the thermopile so constructed with a galvanometer, and thus elaborated an instrument in which the indications of the galvanometer give measures of the radiation incident on the thermopile.

Melloni and Forbes used this instrument in their

researches on radiant heat (1831–40), and thereby established the fact that heat radiated from hot bodies obeys the same laws of reflexion, refraction, polarization, etc., as light.

Of more modern instruments it is difficult to say whether the radio-micrometer of Boys (1887) or the bolometer of Langley (1881) gives the better results. In the radio-micrometer Boys has ingeniously joined the thermo-electric couple and the galvanometer into one instrument of a highly sensitive kind.

Langley's bolometer or radiation-measurer has been more extensively used in spectroscopic work. It consists of a narrow strip of metal specially prepared; it is connected in an electrical circuit with a galvanometer and other appliances so that changes in its electrical resistance can be measured with the greatest accuracy. When radiation falls upon the small metal strip its electrical resistance changes, and one can infer from the measure of its resistance at any moment how much radiation is incident upon it. With such an instrument Langley not only investigated the positions of the dark lines in the spectrum of sunlight, but also estimated the intensity of radiation on either side of the lines at numerous points along the solar spectrum as far as wavelength 150,000.

In such investigations a spectrum of sunlight is formed in the proper way by means of a spectroscope provided with prisms and lenses made of rock-salt, which is peculiarly transparent to heat rays (diathermanous). The narrow strip of the bolometer is then set in the spectrum in the focal plane of the camera, parallel with the lines in the spectrum, and is gradually moved along the spectrum. When a bright piece of spectrum falls on the strip its resistance is altered considerably; when a dark line falls on the strip, the effect is much less. We see at once what a large range of spectrum there is to which we are blind. The bolometer has been made to give its record of parts of the spectrum that we *can* see, and the result is

that we believe its indications even when we have to leave the "seeing" entirely to it. Langley's ultra-red spectrum is thirteen times as long as the visible spectrum; the dark lines appear like irregular little ripples on the sweeping curve that shows how the energy is distributed along the spectrum. The general form of the curve (Fig. 42) is of great import, since it gives us the means, as we shall presently see, of estimating the sun's temperature.

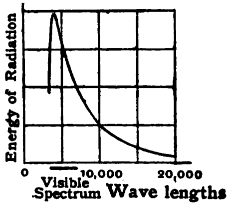


FIG. 42.

Radiation of hot solid bodies at different temperatures.

The radiation of a hot body only becomes visible when its temperature is about 400° or 500° centigrade. Abney has, it is true, prepared photographic plates sensitized in such a way that they were sensitive to the ultra red radiations emanating from a kettle containing boiling water. He has thus photographed a kettle in a dark room, utilizing only the dark heat radiated from the hot kettle itself. This dark radiation can be investigated with as great certainty by means of the bolometer as that radiation which has wavelengths that happen to affect our eyes.

In 1892 Paschen began a series of bolometrical investigations of the spectrum (visible and invisible) of the radiation emitted by glowing solid bodies at various temperatures. He measured the radiation of glowing platinum, glowing oxide of iron, glowing oxide of copper, lampblack and various sorts of carbon at various temperatures. He found strong evidence of the existence of law regulating the emission of radiation. His method was, to measure the intensity of radiation at many points in the spectrum given by a hot body at some fixed temperature; to repeat this

process at many other temperatures; to test the agreement of the experimental results with theory.

The subject was also attacked shortly afterwards (1898) by Lummer and Pringsheim, Kurlbaum and others, and the joint result is a splendid advance in our experimental knowledge of the laws of radiation of solid bodies.

Experiment shows that at any given temperature the amount of energy radiated by a glowing body depends on the material of the body and on the nature of its surface. Some bodies radiate much more copiously than others, but if they are arranged in order of their radiating power, they seem to approach a limit which suggests the existence of a *best* radiator for that temperature.

Theory shows that if bodies of various radiating powers are *surrounded by an enclosure* and kept at a fixed temperature, a state of equilibrium of radiation will be reached in that enclosure, such that a definite quantity of radiation will pass across a unit surface (*e.g.* a square centimetre) wherever that surface be placed in the enclosure, no matter whether it be close to a bad radiator or a good radiator amongst those bodies which are in the enclosure. If the unit surface is near a body which is a bad radiator, then the reflecting, diffusing and transmitting powers of the body are so related as to make up the total quantity of radiation to a fixed limiting value which depends only on the temperature of the enclosure and is independent of the position of the unit surface across which the radiation passes.

Thus theory shows that at any fixed temperature no substance can by virtue of its temperature radiate a greater quantity of heat per unit of its surface than passes through a unit area placed anywhere inside a hollow enclosure containing material substances maintained at that temperature. We may experimentally study the radiation inside such an enclosure by piercing a small hole through its wall and examining

the nature of the radiation that emanates from it whilst its temperature is kept constant. Such radiation is called complete or perfect radiation, and, as such, would be given out by a perfect radiator or perfectly black body, if such a body could be found. We can infer what its radiative properties are by studying the radiation emanating from the hole in the wall of the hot enclosure.

The experimental method is to use a carefully made enclosure which can be heated by means of a powerful electric current circulating round it and can be maintained at any temperature by regulating the current, so that the current takes into the enclosure as much heat as will make good the total loss of energy by radiation at that temperature. The higher the temperature the greater the current required to maintain it constant. A special thermo-electric thermometer is used to measure the temperature of the enclosure and to indicate its constancy at any desired degree of hotness. A small hole in the wall of the enclosure is made the source of radiation to be studied; and care is taken to avoid by means of screens the contamination of any radiation except that passing out of the hole. One form of enclosure is a carbon tube, the walls of which are made to carry a powerful current, which renders the tube red hot or white hot. The tube is surrounded by firebrick, which in turn is surrounded by asbestos. A carbon wad is placed in the middle of the tube; one end is also closed; the other end is left open to serve as the hole through which the radiation escapes.

The radiation thus obtained is allowed to fall on the slit of a specially constructed spectroscope; and a spectrum extending far into the ultra red is formed. A bolometer is then employed in measuring the intensity of radiation at many points in the spectrum, and thus the distribution of energy is investigated.

Difficulties arise from the fact that the spectrum has been formed by apparatus which itself exerts

influence on the amount of radiation which passes through it. The prism absorbs some of the radiation; the air, the moisture and small traces of carbonic acid in the air absorb special parts of the radiation; the prism makes a spectrum which is too extended in some parts and too contracted in others. Allowances have to be made for all of these elements of error. The work of many investigators is utilized.

The experimenters have been led by the theoretical considerations put forward by several workers (notably Boltzmann, Weber, W. Michelson, Wien, Rayleigh, Planck, Larmor and others who have developed the theoretical side with as much vigour and power as the experimenters have shown in making the observations) to compare the results of experiment with the various theories suggested, and they find that there is one mathematical expression that fits their results better than any other. It is of comparatively simple form from a mathematical point of view, but we must be content here to represent the results graphically.

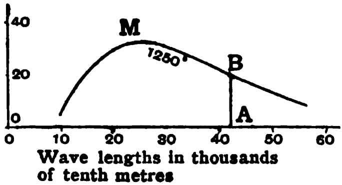


FIG. 43.

It is found that at any one temperature, whatever it be, the radiation is greatest at a definite part of the spectrum, and on either side of this part the radiation falls off according to a perfectly definite law. This statement is illustrated by Fig. 43, which represents diagrammatically the results obtained at the temperature 1250°. Along the horizontal line points are marked off representing the position in the spectrum by reference to the wavelength of the radiation. Thus the point 50 means that part of the spectrum where radiation of wavelength 50,000 tenthmetres is recorded. The small range of the visible spectrum

is indicated in the figure by the dark line between 0 and 10; thus it is seen that the work deals with a large tract of spectrum in the ultra red. At each part of the spectrum a line like AB is drawn to represent by its length the intensity of radiation recorded by the bolometer; the ends of such lines are joined by the dotted curve, which accordingly shows how the intensity rises and falls from one end of the spectrum to the other.

It rises to a maximum at M and falls off on either side. Now M corresponds to a part of the spectrum which in the case illustrated by the figure deals with radiation of wavelength 23,000. Thus at temperature 1250° we have a maximum of radiation at wavelength 23,000. Such a curve is called an energy-distribution curve, for it shows how the energy of radiation is distributed in the spectrum according to wavelength.

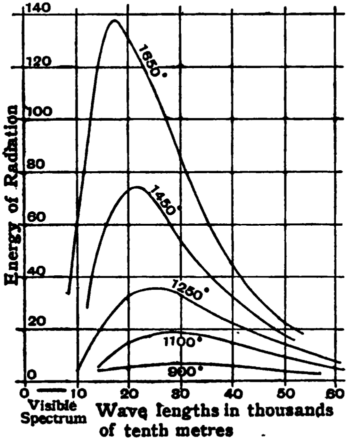


FIG. 44.

Similar curves represent the results at other temperatures. Fig. 44 is taken from Lummer and Pringsheim's observations. The numbers given under the maximum in each curve indicate the absolute temperature of the radiator for that curve.

One sees at a glance not only how rapidly the radiation in every part of the spectrum increases as the temperature rises, but also that the position of the maximum of radiation moves along the spectrum

towards the shorter wavelengths as the temperature rises.

Paschen was the first to find experimentally that the maximum moves along the spectrum in such a way that the product of the wavelength and the temperature is constant; in symbols, the law is stated thus—

$$\lambda_{max} \times T = \text{constant} \quad (3)$$

where λ_{max} means the wavelength corresponding to the maximum of radiation at the temperature T. Wien deduced the same law from theory.

In ordinary cases, a temperature such as that described as 15° centigrade (which is the same as 59° Fahrenheit) is measured from the freezing point of water which is called 0° C. For the purposes of this investigation it is convenient to reckon from a point 273° lower, viz. the absolute zero of temperature. The temperature 15° C. corresponds to 288° Abs. Using the absolute temperature scale and measuring λ_{max} in tenthmetres Paschen's result may be stated

$$\lambda_{max} \times T = 28{,}800{,}000.$$

Hence, if Paschen and Wien's Law be true at such low temperature, at the absolute temperature 288° radiation of wavelength 100,000 tenthmetres is the most intense in the spectrum. This corresponds to invisible radiation in the ultra red, far beyond the range represented in Fig. 44.

Again, if Paschen's Law be true at high temperatures, at the temperature 2880° Abs. which is far above that at which iron (1600°) platinum (1700°) or even iridium (1900°) melt but is not as high as that of the electric arc (4000° Abs.), the maximum would have moved to wavelength 10,000 tenthmetres which is the limit reached by Abney in photographing the ultra red in the solar spectrum. Paschen has experimented up to the temperature 1557° Abs.: Lummer and Pringsheim in their investigations have dealt with the temperature 2000°.

Estimation of the temperature of a body from study of its spectrum.

If we may assume that the law is universally true, then if we can find the position of the maximum of radiation in any spectrum, we may infer the temperature of the source. Thus Paschen adopting the value deduced from Langley's observations for the wave-length of the maximum of radiation in the solar spectrum, viz. about 5000 tenthmetres, has inferred that the temperature of the sun is 5530° centigrade. It is to be noted that these values are deduced from observations of the spectrum of the light of the sun after it has passed through the various strata of absorbing gases surrounding its photosphere. We cannot deduce anything about the temperature of the interior of the sun from observations of this sort.

The experimenters have also compared the energies of the maximum radiation at various temperatures, and find that the maximum increases with the fifth power of the absolute temperature. Thus if the temperature is doubled, *e.g.* if it rises from 304° Abs. (about the temperature of the human body) to 608° Abs. (the melting point of lead), the maximum radiation increases not two-fold but $2 \times 2 \times 2 \times 2 \times 2$-fold, that is 32-fold, whilst the position of the maximum moves along the spectrum from the wavelength 94,000 to 47,000 tenthmetres. Fig. 45 represents graphically the law, which in symbols is expressed thus :—

$$E_{max} = T^5 \times \text{constant}$$

and in words thus : the energy emitted at that part of the spectrum for which the radiation is a maximum varies as the fifth power of the absolute temperature. The curve is drawn so that the ordinate AE drawn at any point A is 32 times as long as that drawn at a point B, which is only half as far from the origin O.

One of the consequences of the laws found to regulate the emission of radiation by hot bodies is that the

total radiation emitted by a "black" body or perfect radiator varies as the fourth power of the absolute temperature. This law is the same as that deduced by Stefan in 1878 from all the experimental knowledge then at his disposal, and it was later established by Boltzmann on theoretical grounds. It was known as Stefan's Law and has been confirmed not only by Paschen's work but also by Wilson and by Lummer and Pringsheim. Thus, if the temperature (Abs.) of a perfect radiator is doubled or trebled, the energy of the *total* radiation is increased 2^4-fold (that is $2 \times 2 \times 2 \times 2$ or 16-fold) or 3^4-fold (that is $3 \times 3 \times 3 \times 3$ or 81-fold).

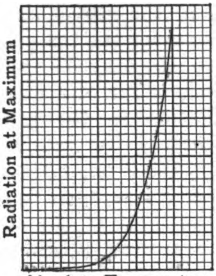


FIG. 45.

CHAPTER XIII

LAW IN THE SPECTRUM—RHYTHMICAL RELATIONS BETWEEN THE WAVELENGTHS OF LINES IN DISCONTINUOUS SPECTRA.

HELMHOLTZ, in his celebrated researches on vowel sounds, discovered that the difference between the sounds Ah and Oh sung on the same note depends on the fact that the note is not a pure tone in either case, but a compound of related tones with different relative intensities in the two cases. By means of resonators made to enforce the audibility of special pure tones, he was able to analyze the vowel sounds and so to prove that the difference between them depends upon a difference in the relative intensities of "harmonics" accompanying the fundamental

tone. Two vibrations are said to be in harmonic relation when their frequencies are to one another in the ratio of whole numbers; thus two notes differing by an "octave" have frequencies in the ratio of 1 to 2; in a "fifth" the ratio is 2 to 3. The harmonics of a fundamental tone have frequencies 2, 3, 4 . . . times as great as the fundamental tone.

The question arose in the early days of spectrum analysis whether similar harmonic relations exist between the various components of radiation in a source of light. Johnstone Stoney pointed out in 1871 that the three lines then known in the spectrum of hydrogen are harmonically related, and that the vibrations corresponding to the three lines might be called the 32nd, 27th and 20th harmonics of a certain fundamental vibration. Several investigations of this kind were put in hand with some semblance of success in the search. Schuster, however, in 1881, pointed out how entirely illusory such semblances may be, depending as they may upon fortuitous coincidences.

In 1885, Balmer, taking the measurements made by Ångström of four hydrogen lines, showed that a remarkable numerical relation existed between the wavelengths. He pointed out that each of Ångström's measured wavelengths, viz.

$$6562{\cdot}10 \qquad 4860{\cdot}74 \qquad 4340{\cdot}1 \qquad 4101{\cdot}2$$

bore to the wavelength 3645·6 ratios denoted by the fractions

$$\frac{9}{5} \qquad \frac{4}{3} \qquad \frac{25}{21} \qquad \frac{9}{8}$$

(the number 3645·6 was chosen because it gave these simple fractions with small numerators and denominators). If the second and fourth fractions are written in other forms of equivalent value, these fractions become

$$\frac{9}{5} \qquad \frac{16}{12} \qquad \frac{25}{21} \qquad \frac{36}{32};$$

$$\frac{9}{5} \qquad \frac{16}{12} \qquad \frac{25}{21} \qquad \frac{36}{32}$$

it is clear that the numerators are squares, viz.

$$3^2 \qquad 4^2 \qquad 5^2 \qquad 6^2$$

and the denominator in each case is less than the numerator by 4,

$$\text{or} \quad 3^2-4 \qquad 4^2-4 \qquad 5^2-4 \qquad 6^2-4.$$

Thus the wavelength of any of these four lines of hydrogen may be deduced from the expression,

$$\lambda = 3645{\cdot}6 \times \frac{m^2}{m^2-4} \text{ (Balmer's series)}$$

if we substitute for m the proper whole number (3, 4, 5 or 6) and do the arithmetic.

If the series is continued in the same way as above, only putting the next whole numbers after 6 in place of m, we should get lines at wavelengths found by multiplying 3645·6 by the fractions

$$\frac{7^2}{7^2-4} \qquad \frac{8^2}{8^2-4} \qquad \frac{9^2}{9^2-4} \qquad \frac{10^2}{10^2-4}$$

that is by

$$\frac{49}{45} \qquad \frac{64}{60} \qquad \frac{81}{77} \qquad \frac{100}{96}$$

namely,

3969·65 3888·64 3834·98 3797·5.

After inquiries Balmer learnt that, five years before, Huggins had found lines in the spectra of certain stars and had from their appearance attributed them to hydrogen. They had wavelengths

(3969) 3887·5 3834 3796;

the one in brackets was found later.

Balmer's remarkable relation of very simple form is found to represent the whole series of lines that we now ascribe (see page 75) to hydrogen, values of m up to 31 being used. The rhythmical series which it indicates is shown in Fig. 46; which is based on Huggins' photograph of the spectrum of Rigel.

The search for similar series in the spectra of other chemical elements was then taken up by Kayser and

Runge in 1888, and very soon afterwards by Rydberg, the former observers making new and very careful determinations of the wavelengths of lines in many spectra and pushing their researches far into the ultra violet part of the spectrum. The importance of extending researches in the ultra violet had been well shown by Hartley's work, in which he had found characteristic groupings of lines in triplets or pairs in definite spectra and some resemblances between the groupings of the lines in the spectra of allied chemical elements.

Kayser and Runge found that the lines of the alkali metals, lithium, sodium, potassium, etc., showed signs of orderly arrangement, and after some ex-

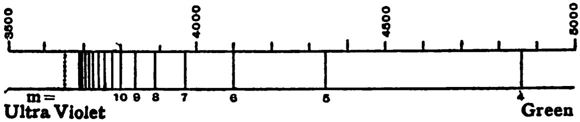


FIG. 46.

perimenting, they chose a simple mathematical expression as suitable for representing it. We will not follow them further except to illustrate graphically how the mathematical analysis separates out the orderly arrangement from what seems chaotic disorder in the sequence of bright and faint lines in a range of spectrum which does not go far into the ultra violet.

Line *a*, Fig. 47, represents the spectrum of Helium. The lines in the visible part of the spectrum are arranged, as one might judge from a first inspection, without any regard to brightness or spacing, but in the ultra violet some appearance of orderliness is at once obvious. Runge and Paschen in 1895 found that the spectrum was the resultant of the superposition of six series of lines, for each of which a simple mathematical relation had been discovered;

two sets of principal series, each accompanied by two subordinate series. In Fig. 47, the spectral lines corresponding to the various series are picked out in the rows lettered *b*, *c*, *d*, *e*, *f*, *g* beneath the complete spectrum shown in row *a*. This spectrum of helium has been chosen for description, for it is one of the most remarkable cases illustrative of the mathematical analysis into series: every line in the spectrum is accounted for; in each series there exists between the brightness of the lines a simple relation, namely, the brightness always increases as the lines get nearer to the red end; and each series

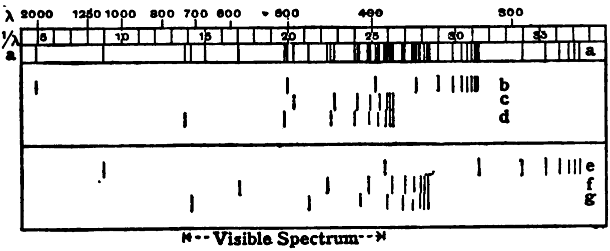


FIG. 47.

consists of lines, whose spacing becomes less and less as they approach the ultra violet, till they reach a limit beyond which there are no more lines belonging to that series.

Kayser and Runge's work on the metallic elements has shown that all the alkali metals show spectra in which the lines, though seemingly distributed without regularity of spacing or intensity, can be separated into three series, each exhibiting a regular rhythmical relation similar to that above described. Kayser and Runge found that the series were further distinguished by the appearance and character of the lines. Liveing and Dewar had, in 1883, called special attention to the fact that in most line-spectra some of the lines are sharp, some are ill-defined and

show a tendency to be winged on one side, others are more easily "reversed" (reversal being the name given to the appearance of a dark central core along the middle of a bright line). Kayser and Runge found that in the three series of lines in the spectra of the alkali metals, the *principal* series comprises the strongest and most easily "reversible" lines, whilst one of the *subordinate* series includes strong diffuse lines and the other subordinate series is composed of fainter but sharper lines. Moreover, the lines are all double, the separation of the pairs obeying simple laws, which are different for the principal and subordinate series.

Kayser and Runge have succeeded in finding series in the following elements :—

Elements.	No. of Series.	Peculiarities.
Li, Na, K, Rb, Cs	one principal, two subordinate	lines double
Cu, Ag, Au ...	two subordinate	lines double, except in Au
Mg, Ca, Sr ...	two subordinate	lines triple
Zu, Cd, Hg ...	two subordinate	lines triple
Al, In, Tl ...	two subordinate	lines double

Runge and Paschen have also found series in the spectra of the elements O, S, and Se.

It must be noted that while series have been found connecting some of the lines in these various spectra, other lines often remain unaccounted for. The importance of the successes in finding series is greatly increased by the fact that it appears that elements may be grouped, spectroscopically, with results that agree closely with Mendeljeff's classification according to chemical properties.

Law in banded spectra.

If order is discoverable in spectra that disguise it so much as the line spectra of the metals, it is not surprising that mathematical expressions have been

found for the law of arrangement of lines in such obviously orderly spectra as banded spectra. Already, in 1882, Alexander Herschel and Piazzi Smyth had found a law for the order in the arrangement of the bands in the nitrogen spectrum and of the lines in the green band attributed to carbonic oxide. Herschel adopted the method of naming a line by using *wavenumbers* instead of wavelengths in his calculations; the suggestion originally emanated from Stoney in 1871, and the practice has been followed almost universally in recent work. The "wavenumber" is the number of waves in a definite distance: a centimetre is very commonly taken; thus when the wavelength is large, fewer of them are required to fill the centimetre, and hence the wavenumber is small.

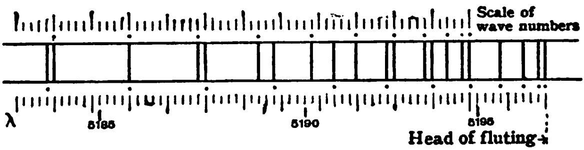


FIG. 48.

Herschel found with respect to the CO band, that the first forty-four lines can be arranged in several series, each of which presented an arithmetical progression in *wavenumbers*, whilst the different series are displaced relatively to one another. The matter is illustrated in the Figure, dealing with 21 lines in the band.

In 1885–91 Deslandres made an extended investigation of the spectrum of nitrogen and other spectra; and his results show that Herschel's Law, discovered in a small range of spectrum, holds true through a large range, and that the appearance of law in each single band or group of lines may be resolved into the existence of law through the whole spectrum; for whilst the eye picks out not only groups of lines to form a band, but also groups of bands to form recurrent systems of bands, the

mathematical analysis shows that a few series of lines, each extending through the whole spectrum, may when superposed account for every line in every group (Fig. 49).

What the physical system may be, that is capable of giving out vibrations of this kind of belinkedness remains to be discovered. Whatever the constitution of the particles of gas may be, that conspire to give the indications of vibration which we analyze in the spectroscope, we see that the vibrations must be far more complex than those that Helmholtz had to do with in analyzing vowel sounds into fundamental tones accompanied by harmonics.

It has been suggested that the luminous molecule

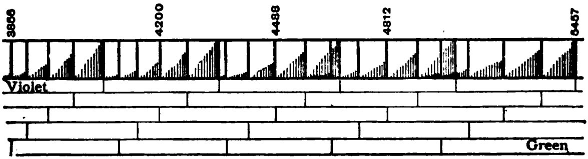


FIG. 49.

in its simplest mode of vibration cannot emit less than the whole of one series of lines, such as we have above described; and the spectroscope analyzes that mode of vibration into pure "tones" and presents them to us as single lines related to one another as we see them related in a series. However that may be, we see that mathematical analysis of the results of spectroscopic analysis shows (i) that in line spectra the superposition of a few series of an extended order may give us a spectrum in which order is hard to find because of the wideness of the scale; and (ii) that in banded spectra the superposition of a few series of comparatively closely serried lines may give us a spectrum in which the orderliness is the most striking feature. But the similarity of constitution of the two kinds of spectra

ends with this idea of superposition of series of lines; for the "band-series" differs wholly in character from the "line-series." The "line-series" consists of lines that are more and more closely serried, as the ultra violet part of the spectrum is approached; and the lines diminish in brightness at the same time as they approach one another in spacing, till the limit of the "line-series" is formed by a countless number of very faint lines. In "band-series" the lines are more closely packed together in the red and are fainter there than in the violet. Moreover, there is the widest difference between the limit of a line-series and the head of a band; for the higher the spectroscopic power used the more numerous are the lines found in the limit of a line-series and the fainter do they become: whereas in the head of a band the use of high power merely proves that there are a finite number of lines arranged in curious order.

Thus two distinct kinds of series of lines have been empirically discovered; it remains for future workers to find out the conditions under which they originate.

CHAPTER XIV

DIFFRACTION BY A NARROW SLIT—DIFFRACTION GRATINGS—MEASUREMENT OF WAVELENGTHS

More than a century ago the opponents of the wave theory of light urged against it that, if it were true, we could not have rectilinear propagation of light through narrow openings; the waves in passing through would spread out and bend round the edges of the opening. This is exactly what we find they actually do, if we take steps to make the opening small enough, not wider than a few wavelengths of light. When we call down a passage towards an open door and a room at the end of it, the sound

spreads out and is heard in every part of the room; but the spreading of the waves of sound round the edges of the doorway would not take place unless the width of the doorway and the length of the waves of sound were nearly of the same magnitude. Light travelling down the passage illuminates only the wall opposite the door; it does not spread round the edges of the doorway; the waves of light are infinitesimally small compared with the width of the doorway. If we make a doorway of width not greater than a few wavelengths of light, then the light actually does spread out like sound.

Let us proceed to make such a doorway, and study some of the phenomena of *diffraction*, as this bending of light round the edges of opaque screens is called. Lay a piece of tin foil about an inch square on glass and, after smoothing it carefully, stick the foil with gum on the glass; then make a single and clean straight cut about $\frac{1}{4}$ of an inch long in the middle of the foil with a very sharp knife. (Fig. 50.) A very narrow aperture in an opaque screen is thus provided, in fact the required doorway.

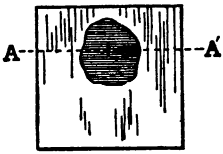


FIG. 50.

Now set a lighted candle in front of a smooth black background and look at the flame (first from a distance of about a yard) through the narrow aperture, holding the tin foil close to the eye; and note the following phenomena.

Firstly, if the long narrow aperture is horizontal, you will be able to see the vertical edges of the flame and of the candle distinctly, but the top and bottom of the flame will be indistinct, and likewise the top edge of the wax. We see that, by limiting the aperture of the eye by a narrow horizontal slit, vertical lines appear distinct, but horizontal lines as blurred outlines.

Secondly, if the candle is viewed through the aperture held vertical, it is possible to see the top edge of the wax distinctly, but the flame appears ill-defined; it is apparently widened out and there are dark and coloured bands on either side of it. (Fig. 51.) These alternations of dark and bright bands on either side of the central bright band are called "diffraction bands" and they are produced by the superposed effects of the waves of light coming through the narrow opening. The very fact that a dark band can result from the superposition of illuminations is taken as one of the signs that light is of the nature of waves and not of the nature of small particles emitted from the source; for whilst we cannot satisfactorily conceive that the superposition of particles on particles should result in the production of considerable effect (to wit, a bright band) in one place and also of no effect (to wit, a dark band) in another place, yet we can readily understand that such contrasted effects may arise from the superposition of waves; for we have only to admit that "no effect" (dark band) is produced at places where crest is superposed on trough resulting in no motion or disturbance, and that a bright band is the result of superposition of waves in similar phase, crest on crest and trough on trough, resulting in considerable motion or disturbance. We will revert later to the appearance of colour at the edges of the bands.

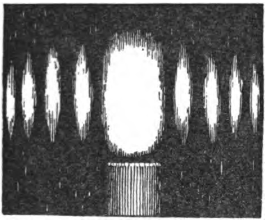


FIG. 51.

Let us consider two aspects of the phenomena described: (i) the apparent limitation of the power of the eye to see distinctly; (ii) the utilization of the diffraction bands for the measurement of wavelengths.

We see in the way that the light of the candle has

been spread out into these bands (Fig. 51) an indication of the mode in which the defining or resolving power of the eye has been reduced. The defining power of the eye depends on the size of the aperture of the pupil just as the defining power of a telescope depends on the size of the aperture of its object-glass. The pupil of the eye is about $\frac{1}{5}$ of an inch in diameter, or roughly speaking about 10,000 wavelengths of light. Light passes through it without appreciably spreading out and we get well-defined images. If the pupil is limited by interposing the foil with a narrow vertical aperture in it, which leaves the vertical aperture of the pupil the same as before, but diminishes the horizontal aperture until its width is only a few wavelengths, then the waves spread out in horizontal directions and give blurred images of vertical lines, whilst a horizontal line drawn out along its own length looks relatively sharp. If the pupil is limited in all directions equally, by interposing a card with an exceedingly small round pin-hole in it, then all objects look blurred and no lines are distinctly seen. For distinct vision of defined lines and points we require broad wavefronts, such as can pass in at the full aperture of the pupil; and for yet distincter vision we must use the still larger apertures of telescopes to aid the eye (page 67).

It is hardly possible here to give a complete account and explanation of diffraction phenomena, and the attempt is only made to bring a few notable phenomena before the reader in order that he may gain some insight into the reasons for believing in the possibility of measuring such infinitesimally minute things as we have stated the wavelengths of light to be.

Let Fig. 52 represent on an enlarged scale a cross section (along the line AA′ in Fig. 50) of the glass and foil and aperture (the width of the aperture being much exaggerated). We describe the diffrac-

tion bands by saying that when the light from the candle (which is supposed to be far beyond the top of the page) passes through the aperture, the illumination is bright at and near O, but falls off on either side gradually till there is darkness at P_1; then it brightens up as we go from P_1 to P', and falls off to darkness at P_{11}, and so on. The eye placed close behind the aperture receives the light in the appropriate directions and refers it to origins near the candle in the directions So, Sp_1, Sp', etc.; the phenomena seen are on the same scale as they would be if the light after passing through the aperture were received on a screen placed as far behind the aperture as the candle is in front.

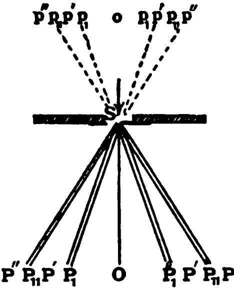


Fig. 52.

The position of P_1, the point where the band is dark, is decided by the direction of the lines drawn from the edges of S in such a way that P_1A is longer than P_1B by two half wavelengths (Fig. 53). The position of P_{11}, where the second dark band comes, is such that $P_{11}A$ is longer than $P_{11}B$ by four half wavelengths. In intermediate positions, as at P' and P'', the bands are bright. The law is definite.

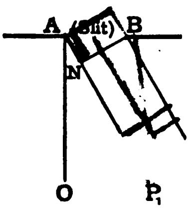


Fig. 53.

We do not here attempt to explain the phenomena and the law further than to state that it is the result of the summation of effects of wave disturbances coming from every point in the aperture AB. When the difference between P_1A and P_1B, which is denoted by AN, is two half wavelengths it involves that the disturbance from A arrives at P_1 exactly

half a wavelength behind that arriving at P_1 from S, the middle of the aperture; and similarly every point in one half of the aperture emits a disturbance exactly opposite in effect to that emitted by a corresponding point in the other half of the aperture. Thus the total effect at P_1 is nil, *i. e.* darkness. In intermediate positions like P′, P″, we have bright bands (Fig. 54).

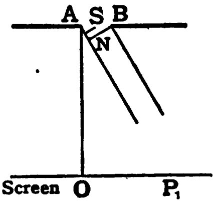


FIG. 54.

Let us look at the simple geometry of the case, and see how we can find the number of wavelengths that would span the aperture AB. The difference between P_1A and P_1B is denoted by AN (Fig. 53, the lines P_1A and P_1B are incompletely drawn in order to indicate that OP_1 is represented too close to AB); the angle between P_1A and AO is equal to the angle between AB and BN. Hence in the right-angled triangles P_1AO and ABN, the length OP_1 bears to AP_1 the same ratio as AN bears to AB. Thus we see that by comparing OP_1 with AP_1 we can compare AN with AB; or in other words, the whole wavelength with the width of the aperture.

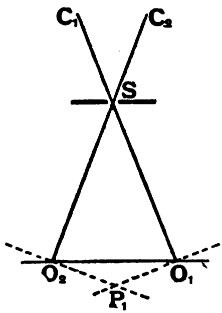


FIG. 55.

To make the comparison experimentally in a simple manner let the reader now set up two candles, side by side, six inches apart, one being about two inches taller than the other; he will be able (i) to observe through the narrow vertical aperture the two diffraction patterns one above the other, and (ii) to arrange, by going to the proper distance from the candles, that the first lateral dark band on the right hand of the

lower flame comes immediately under the first lateral dark band on the left hand of the upper flame. He should then be able (iii) to satisfy himself (Fig. 55) that the aperture he has used contains four times as many wavelengths in its width as there are feet in the distance between his eye and the candles. He will then realize that the wavelength of light is a very small thing.

An accurate modification of this method of comparison may well serve for an estimate of the width of a narrow aperture when the wavelength of light is known, but it has to be developed, as we shall see, on other lines before it becomes possible to adopt it for accurate measurement of wavelengths of different colours.

The appearance of colours at the edges of the bands is due to the composite nature of the candle light; each component produces its appropriate diffraction bands. The shorter the wavelength the smaller will be the distance of the first dark diffraction band from the centre. Thus violet and blue, being of shortest wavelengths, have dark diffraction bands closer to the centre than green, yellow and red; thus the edges of the central band, robbed of their violet and blue components, look more orange than the central part. Again the violet and blue colours have their first bright diffraction bands nearly coincident with the first dark bands of the red. This incommensurability of the bands in different colours is the cause of the appearance of colour in the bands. If monochromatic light, such as that of a salted spirit flame, is used instead of the candle the bands alternately dark and bright are seen devoid of all colour.

These broad ill-defined diffraction bands are not easy things to measure with the accuracy required for wavelengths. Let us now consider how we can make them appear as narrow well-defined lines, when light from a narrow source (much narrower than the flame of a candle) is observed through a narrow

aperture. Such an achievement would enable us to make our measurements with all the precision attainable in measuring distances between sharp lines on a clearly divided scale instead of between blurred patches. We can attain this end by putting several hundreds or thousands of such narrow apertures side by side, close together, parallel to one another, and separated in a particular manner; we thus combine narrow wavefronts and secure the advantages of broad wavefronts, as we shall now indicate.

Fig. 56 represents light coming from a distant slit (not shown) and falling perpendicularly, as indicated by the arrows, on several narrow openings of the same width and separated by equal narrow opaque partitions; it is not necessary that a partition should be of the same width as an opening, but every pair (one opening and one adjacent partition) should have the same total width. Some of the light goes straight on through each of the openings in the direction AO (the case of the direct central beam is not illustrated in the figure), and the small wavefronts that get through pass onwards as if belonging to one broad wavefront; if they fall on an object glass it shows in its focal plane a defined image of the distant slit from which the light emanates. The definedness of this image depends on the *width* of the wavefront coming from the series of openings; and the position of the image is central behind the openings.

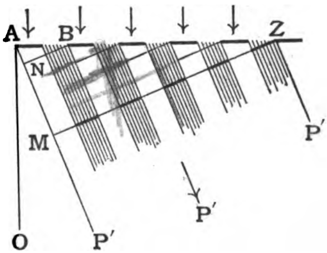


FIG. 56.

Now consider a lateral beam made up of light diffracted from each opening in the way indicated by the shaded beams in Fig. 56; and let the direction of the beam be such that the distance AN represents one whole

wavelength where BN is drawn perpendicular to AN from B, the end of the next partition similar to A, and AN is drawn in the direction of the beam considered. Then we have from each opening a small wavefront passing along in a direction parallel to AP′, and each small wavefront is retarded by a whole wavelength behind its neighbour on the right. And since through every opening a series of waves are passing, each belated small wavefront finds a neighbour that is in line and, so to speak, "in step" with it, and thus a complete new and broad wavefront like ZM is formed. When a succession of such broad wavefronts falls on an object-glass, a well-defined image of the distant source of light is formed. Thus, in addition to the central image formed in the direction AO, we have a first bright lateral diffraction line formed in the direction AP′. As a result of the mutual action or "interference," as Young called it, of disturbances from neighbouring openings, practically no light of the same wavelength passes in directions intermediate between AO and AP′.

Similarly a second and a third bright diffraction line are formed in directions such that the retardations analogous to AN are two and three whole wavelengths; and practically no light of the same wavelength passes in intermediate directions. Thus by a proper combination of narrow openings the diffraction bands in any one colour or wavelength can be made very sharp and defined images of the original source of light.

Experiment shows how completely this gathering up of the light from broad bands into narrow lines can be brought about. The strict theory of the phenomena rests on mathematical reasoning based on principles laid down by Huyghens (1629–1695), Thomas Young (1773–1829) and Fresnel (1788–1827). Such a series of openings and partitions as we have described above is called a "diffraction grating."

Fraunhofer, that remarkable pioneer in experimental optics, was the first to make a diffraction grating, and in 1821 he had measured the wavelength of the D line and announced to the Munich Academy that its value was 588·8 millionths of a millimetre (5888 tenth-metres). His grating was made by winding very fine uniform wire round a frame, which was constructed by fixing together (Fig. 57) two parallel screws to serve as top and bottom of the frame and two bars of metal to serve as the sides. The wire was soldered in position on the screws and the joints of the frame were also firmly soldered. Then the frames were sawn in two along the axes of the screws and the sides, and thus two wire gratings were made. The wires are the opaque partitions; the intervals between them are the narrow apertures. Fraunhofer, and later on also Nobert and Rutherford, made gratings by using a diamond point to rule fine parallel lines very close together and evenly spaced on the surface of a plate of glass.

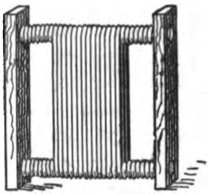


FIG. 57.

Such gratings are used as follows: A narrow slit and collimator, such as are used in a spectroscope, are fixed in a horizontal position, and a telescope or viewing tube is also set up horizontally so as to point into the collimator; and thus an image of the vertical slit can be seen if light is allowed to pass through the slit and collimator. The grating is now inserted between the object-glasses of collimator and telescope, and is fixed there in a vertical position with the wires or ruled lines parallel to the slit. Means are provided for measuring the angles, through which the telescope may be turned, with the utmost accuracy.

If light of only one wavelength is used, what is seen in the telescope is a narrow bright image of the slit

flanked by narrow fainter images symmetrically placed on either side. If the grating is very closely ruled, it may be necessary, in order that the lateral images may be seen, to turn the telescope to one side or the other through a considerable angle (*e.g.* OSP′ in Fig. 58). If sunlight falls on the slit we get a regular spectrum formed, because the light that gives the images of the slit in different colours is diffracted through angles that depend on the wavelength. The first lateral blue images are nearer to the central image than the first lateral green, yellow and red images. Then by careful measurement of the angles through which the telescope is turned so as to give successive views of the central image (bisected by the cross wires fixed in the focal plane of the telescope) and of lines in the blue, green, yellow and red (also bisected) we can deduce the wavelengths of the blue, green, yellow and red lines chosen, provided we know the width of the element AB of the grating, that is, the interval between two successive wires or rulings. We can determine this accurately by putting the grating under a powerful microscope and moving it sideways through a measured distance, say one inch, and counting the number of lines in that inch.

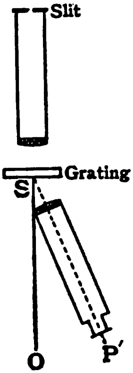


FIG. 58.

Summarizing we may say that the grating enables us to measure the wavelength of any special kind of light by comparing it with the interval between successive rulings on the grating, this interval being in turn compared with some recognized standard of length. The ratio of the wavelength to the interval on the grating is known when the angle OSP′ is measured; for simple trigonometrical considerations show that the ratio is the sine of the angle measured; $\lambda/d = OP'/SP' = \sin OSP'$.

We have hitherto considered gratings which transmit the light through the narrow openings between opaque wires or between the ruled lines on the glass. Even better results can be obtained by ruling lines on a polished plane mirror of highly reflecting speculum metal. The light from the collimator is then reflected from the spaces between the rulings on the mirror in place of being transmitted. In actual use of a metallic grating the observer sets himself free from the restrictions imposed by letting the light from the collimator fall normally on the grating. A new and simple mathematical relation is readily found for application to the case of oblique incidence of light on the grating.

Rowland, of Baltimore, by devoting special attention to perfecting the micrometer screw by which the even spacing of the ruled lines is secured, constructed the most perfect gratings yet made. These gratings were ruled by diamond points on a smooth plane polished metal surface and the lines were ruled so close together that there were 20,000 lines or in some cases even 40,000 lines to the inch. Some gratings were made of such extent that each line was 3½ inches long and the ruling was continued over 6 inches, so that the ruled surface was 3½ inches by 6.

Rowland made a further great advance by ruling lines on a concave polished surface and showed how the grating so formed could be used to give good monochromatic images of the slit without the use of any lenses. With a grating of large dimensions arranged in the way he indicated, his splendid photographic map of the solar spectrum was made, and a scale was engraved at the top of the spectrum to indicate approximate wavelengths along the length of the spectrum, whilst for accurate values of the wavelengths of the individual lines Rowland published a table of wavelengths of 23,000 lines (page 65).

We have seen how several lateral images are formed by a grating, the first ones on either side

corresponding to retardations of single wavelengths, the second to retardations of two whole wavelengths, and so on. We get as many spectra as there are lateral images. The spectrum of the first order on each side is that made up by the close juxtaposition of all the first lateral images in every colour. The second order spectra similarly consist of all the second lateral images in every colour, and so on. Each spectrum is generally brighter than that of next higher order and is also less spread out or dispersed; and since the whole of the light available for the production of all the spectra, as well as the central uncoloured image, is only that which passes in at the narrow slit, it will be realized that diffraction spectra are so much fainter than prismatic spectra that they are only available when the source of light is very bright or else in photographic methods when a long exposure can be given to make up for the feebleness of the light.

The position of a line in the diffraction spectrum depends only on the wavelength and on what may be called the geometrical conditions of the case, whereas in the prismatic spectrum the position of the different lines depends on the refractive indices of glass. Since the relation between wavelengths and the refractive indices of glass is by no means of a simple geometrical kind the scale of the prismatic spectrum changes from point to point along the spectrum in such a way that the conversion of measured positions of the lines concerned into corresponding wavelengths is not a simple matter. But when once the wavelengths of certain well-known standard lines, *e.g.* those of iron vapour in the electric arc, are determined by means of a diffraction grating, a prismatic spectroscope can be calibrated so to speak and the wavelength corresponding with any scale reading in the spectroscope (p. 42) can be readily deduced.

The following table gives the results of various

determinations of the wavelength of the sodium line D_1 as measured in air :—

Observer	Date	Grating made by	Wavelength in tenthmetres
Fraunhofer . . .	1821	Fraunhofer	5888·
Mascart . . .	1868	Nobert	5894·3
Angström . . .	,,	,,	5895·13
Pierce . . .	1878	Rutherford	5896·27
Müller and Kempf .	1886	Wanschaff	5896·25
Bell	1888	Rowland	5896·18

In vacuo the wavelength would be 5897·90 tenthmetres.

CHAPTER XV

VARIATIONS IN THE SPECTRA OF GASES AND VAPOURS

CERTAIN elements give more than one spectrum (page 55). Thus Nitrogen has not only a bright-line but also a bright-band spectrum, both being evoked by electric discharges through the gas. The band spectrum consists of three or even four sets of bands of different appearance; one set entirely in the ultra violet: another set in the ultra violet, violet and blue, sometimes extending even into the green: and another set of narrower bands appearing in the green, yellow and red part of the spectrum. It is possible by varying the conditions under which the gas is made to glow, to vary the amount of overlapping of the sets of bands and also to vary their relative intensity and even to evoke one set without the others. Yet another set of bands have been observed, connected with the glow which at atmospheric pressures surrounds the negative electrode but which, when the pressure of the gas is sufficiently reduced and the electrical discharge is suitably regulated, is found to pervade the whole of the tube in which the discharge takes place. It is believed that there may be several states of aggregation of nitrogen particles, and that each state has its

characteristic spectrum, which is evoked under suitable conditions of temperature, pressure and electrical stress.

Apart from the occurrence of different spectra in connection with a single element, the following variations may be observed in one and the same spectrum under different conditions :—

a. The brightness of all the lines may increase or diminish.

b. The *relative* brightness of the several lines may change.

c. The brightness of the continuous background may change.

d. The width of the lines may change.

e. The position of the lines may change.

The earliest observers rejoiced over the discovery of "unalterable characteristics" in the spectrum of each element. We have now to attach a limited meaning to the word "unalterable." For we find that there is hardly a single characteristic that cannot be altered in one or more of many possible ways. But we are satisfied that general *unmistakable* characteristics appear in the spectra of the elements, whatever the interpretation of changes may be. And, as is usually the case in the advance of knowledge, advantage is sought from the comparatively small disguises of the characteristics; and investigators search for evidence that shall prove that whilst the general characteristics depending on the relative position of lines proclaim the chemical origin of the spectra, the variations in the appearance of the lines and other features may indicate the physical conditions of the substances emitting the spectra, as regards temperature, pressure and mode of excitation of luminosity.

If we consider how many of the peculiar features in the spectra of stars—involving the passage of light through hundreds of miles of glowing atmospheres surrounding bodies probably seldom less

than a million miles in diameter—can be mimicked in great measure in the phenomena we observe in an electric spark an eighth of an inch in diameter, we realize how vast a complexity in the range of conditions is compressed into the compass of the electric spark and how easy it must be to ascribe phenomena to the wrong causes.

The writer of a primer would rejoice if he could definitely state that the observed variations were assignable to a few definite causes, but we must frankly admit that no such final result has yet been attained, at any rate no such result as compels general unanimity among observers. The only course is therefore to describe variations observed in spectra and to attempt to state the various factors in the originating conditions of luminosity.

Brightness and change of brightness in spectra.

It is generally believed that *bright* spectra are connected with high temperature, and that elevation of temperature increases the brightness of the spectrum especially in the regions of short wavelengths, *i. e.* in the violet and ultra violet. By this it must not be understood that all lines in a spectrum are necessarily brightened *pari passu*. From the structure of spectra as evidenced by the discoveries of Kayser and Runge and of Rydberg, relating to the existence of overlapping series of lines, we may expect to find that the lines belonging to different series are affected in different ways. And, moreover, as we recognize the need of regarding the spectrum presented by the spectroscope as capable of being further analyzed by the results of accumulated experience into component spectra superposed and attributable to different groupings of molecules in the source of light, so we must expect that elevation of temperature will be accompanied not only by brightening of some of the component spectra but also, possibly by the obliteration

of others, simply because the grouping of radiating molecules is altered at the higher temperature.

When the spectrum of sodium in the bunsen flame is examined, the only lines visible are the two yellow lines. When, however, the spectrum of sodium in the electric arc is observed other lines become visible; and this is explained generally by the statement that the temperature is higher in the arc than in the flame. Even here we see there are loopholes for error; for not only is the temperature higher but other conditions are also different inasmuch as the electric forces are organized in the arc, though not in the flame; and hence the conditions of excitation of luminosity are different.

There are other changes connectible with the mode of electrical excitation. When the spectrum of a metal as observed in the electric arc is compared with the spectrum observed in the electric spark it is seen that many of the lines are common to both spectra, but that certain lines are much brighter in the spark, and these lines have been called "enhanced lines." Additional interest is given to this variation by the fact that, as Lockyer has pointed out, enhanced lines appear with marked prominence in the spectra of certain stars, *e.g.* *a* Cygni.

Increase of brightness of spectra may also be the result of an increase in the quantity of the molecules engaged in giving luminosity. It may well be that elevation of temperature of a mass of gas brightens spectra as a secondary phenomenon, by the increase in the number of molecules differing from the average state of molecules which defines the temperature of the gas.

Widening of lines and increase in brightness of continuous spectrum.

If the spectrum of a flame such as the oxyhydrogen flame be examined, under conditions in which the pressure can be varied, it is noticed that the width of

the lines varies and the relative brightness of the continuous spectrum varies. Frankland stated in 1868 that lines in the spectrum, originally narrow under conditions of low pressure, may be so much widened by an increase in pressure that they lose the appearance of lines altogether, becoming broad bands and eventually coalescing; in other words, the bright line spectrum is changed into a continuous spectrum. However interpreted this is an observed fact of the utmost importance in its bearing upon the interpretation of the spectra of the sun and stars; the discovery that a gas can give a continuous spectrum has done away with the only strong reason for the belief that in the sun there necessarily exists a solid or liquid core, a belief which held sway, as we have seen, in Kirchhoff's day. Frankland and Lockyer attributed the widening of the lines to increase of pressure; but here, too, are loopholes for error. Deville at once pointed out that with increased pressure in the flames the temperature becomes higher, and the widening might be described as due to elevation of temperature.

Widening of lines can be brought about in other ways. For instance, if electric sparks be passed through ordinary unignited coal-gas unmixed with air, we are able to see that the hydrogen lines are bright in the spectrum of the spark, and by properly manipulating the discharge it is possible to produce either narrow or broad lines; this may be achieved with an exceedingly small change in the nature of the spark. Again, if the sodium lines are observed in the bunsen flame, the yellow lines are seen to widen whenever fresh quantities of salt are injected in the flame and to become narrow when in continued vaporization of the salt the quantities of vapour are reduced in the flame. Here, then, we apparently have widening of lines as the result of increased quantity of vapour without alteration of pressure, except in the sense of partial pressure.

A continuous spectrum can be evoked also in highly rarefied gases. Schuster showed that rarefied oxygen is capable of giving a continuous spectrum. J. J. Thomson records that other rarefied gases rendered phosphorescent by electrical discharges give a continuous spectrum. Newall has observed that certain mixtures of highly rarefied gases, which under similar conditions give a continuous spectrum, can be made to emit bright lines during the process of simple compression of the rarefied gas into a smaller volume.

Increase of pressure and displacement of lines in the spectrum.

As an outcome of the very accurate work inaugurated by Rowland, at Baltimore, it was discovered by Humphreys and Mohler in 1895 that if the spectrum of the electric arc be observed with minuteness under conditions in which the pressure of the surrounding gas can be increased considerably, the position of the bright metallic lines is seen to be shifted in the spectrum. The amount of shift is exceedingly minute, even when the pressure is increased to 10 or 15 atmospheres, but the importance of the observation is undoubted, as bearing both on the question of the effect of pressure, and on the possibility of using the observations for obtaining a gauge of pressure in celestial and other objects. Increase of pressure makes the lines move minutely towards the red end of the spectrum, the change being of the order of a quarter of a tenthmetre for 100 atmospheres.

Displacement of lines in the spectrum and chemical environment of luminous molecules.

Mitscherlich, by allowing a spark to pass from a refractory metal point to the surface of a solution of certain salts, studied the spectra of the salts and obtained in 1862–64 results of very great value and

interest. As an instance of his procedure we may describe the following case. A solution of the chloride of calcium was used and was mixed with a comparatively large quantity of chloride of Ammonium. The last named salt, whilst giving no marked spectrum, is more or less readily dissociated by the passage of sparks, and thus the sparks are formed in an atmosphere of chlorine or hydrochloric acid or both. The spectrum of the spark exhibits bright lines which, though they remind one of the spectrum of the metal calcium, are arranged so far differently that Mitscherlich attributed the spectrum to the *compound*, chloride of calcium. When a bead of chloride of calcium is introduced into a bunsen flame, the flame is coloured red and the spectrum produced is generally attributed to the metal itself; it will be seen that the atmosphere in which the metal is set free in this case must be very different from that in Mitscherlich's arrangement. In the one case it is highly probable that the oxide of calcium is formed, in the other case the chloride is volatilized as chloride. However this may be, Mitscherlich has made out that there is an obvious resemblance between the spectra of the haloid compounds (*i. e.* the chloride, bromide and iodide) of each of the alkaline earths (calcium, barium and strontium). The resemblance is attributed to the fact that the various compounds studied have an element in common. The differences are ascribed to the variations in the restrictions set by the different haloids in combination upon the vibrations of the common element in the act of radiation.

It will be clear that the proper identification of a spectrum with its real origin is a matter of no small difficulty.

Long and short lines, and reversals of lines.

In Lockyer's image-on-the-slit method of observation (page 94), wherein the image of a spark is thrown

upon a slit so that the image of the line joining the metal poles lies along the slit, some of the metallic lines in the spectrum are visible only in the neighbourhood of the poles whilst others stretch nearly along the whole spark. The longest lines are by no means always the strongest. Some metals can be made luminous in the lower temperature of a flame, as well as in a spark; in such cases it is seen that the lines that appear long in the spark are those that appear in the flame.

When an image of the arc is thrown upon the slit of a spectroscope so that the length of the arc is at right angles to the length of the slit, then if the arc be supplied with a mixture of volatilizable substances it is seen that certain lines stretch across the whole width of the arc and appear in the confines of the arc as well as in the middle, whilst other lines appear only in the middle. The interpretation of the phenomena is not without its difficulties because the effects due to the outer strata of the arc are superposed upon those due to the core.

A curious instance of the result of such superposition of effects is afforded by the "reversal" of many of the lines, that is, many of the bright lines are seen to be as it were split into fine double lines by the appearance of a dark line extending along the middle of their breadth. Such reversal of lines is only seen when the implicated line is of considerable width and when the effects of the core and of the outer strata of the arc are superposed; it receives a simple explanation similar in nature to that adopted to explain the dark solar lines, namely, that the relatively cool vapours surrounding the hotter core absorb some of the light coming from the core.

In this brief chapter, it is to be feared, the difficulties of the case are emphasized more than the definite achievements of results. The fact is that the real control of the conditions under which luminosity takes place is far from being in our

possession; the study of the changes is rendered all the harder because the variation of one condition brings about unexpected and almost uncontrollable changes in other conditions.

Consider the numberless molecules taking part in the emission of radiation, which the spectroscope analyzes. If we are dealing with the luminosity of a gas in a vacuum tube, any molecule collides with others at intervals, which, though excessively short in themselves, are yet very long compared with the period of vibration of the disturbance that gives rise to a line in the spectrum. Hence the vibrations in which the waves of light originate take place with undisturbed regularity between successive collisions and are in greater or less degree unaffected by the existence of neighbouring molecules. Under such circumstances the wavelength of the radiations emitted by numberless molecules is practically the same for all; and this is evidenced by the narrowness of the line in the spectrum. Here then the evidence of the spectroscope proves the similarity of numberless molecules, as judged by the uniformity of wavelengths emitted. If, however, the molecules be close together and collide at comparatively small intervals, then the vibrations set up at one instant may be almost immediately interrupted by another collision, and the vibrations meanwhile are performed by the molecule whilst it is under the varying influence of close neighbours; the wavelengths of the radiations emitted by the molecules are accordingly various, and we get in the spectrum lines with diffuse edges. Here the additional evidence given by the spectroscope proves that similar molecules can have their peculiar periods affected by the interference of their neighbours. And again, if the mode of excitation is of a certain kind, we may have such varied conditions of radiation in different molecules, even in a rarefied gas, that we have a confused mass of radiation which the spectroscopic analysis shows

to have a continuous spectrum. Here the evidence is that something in the mode of excitation of luminosity has failed to evoke individuality from the communities of similar molecules or else reduces it down to the average results, such as we find in the radiation of all solid bodies at high temperatures. When the conditions of excitation are such that steady and continuous change is encouraged, as we imagine is the case when chemical changes take place either in flames or under the influence of electrical forces, then we get results that indicate that a large number of molecules conspire towards uniformity of peculiarity.

We know as yet too little of these intimate atomic chemical changes to be able to predict with certainty or to assert with dogmatism what alterations can be expected to be the outcome of the conspiracy when change in a wholly statistical condition like temperature or pressure is made.

We have strong evidence to make us doubt if the simple heating of a gas or vapour in an enclosure can by itself produce luminosity whose spectrum exhibits bright lines, *unless chemical action of some sort is known to be taking place;* we doubt if a gas or vapour can emit bright lines in virtue of its temperature alone. When we insert sodium salt into a flame the light emitted comes from constantly renewed vapour passing through the flame; and in observing the emission of bright lines we are observing a phenomenon which seems to depend on the reiteration of a certain change in the successive molecules of the vapour as it passes through the flame.

It may well be that electrical discharges evoke in the most marked manner the peculiarities we most wish to study, because the forces are either orderly in direction and magnitude as in the electric arc, or orderly in periodic application as in the electric spark.

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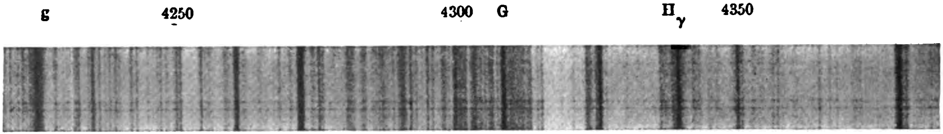
(*See also Table of Contents,* pp. iii, iv)

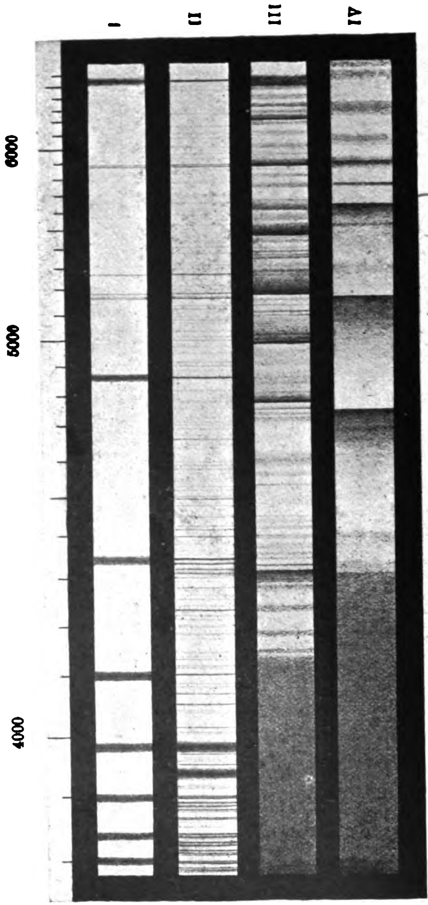
PLATE I.



A. SMALL REGION IN THE VIOLET PART OF THE SOLAR SPECTRUM (*see* p. 59)
(The horizontal streaks are due to specks of dust on the slit of the spectroscope)

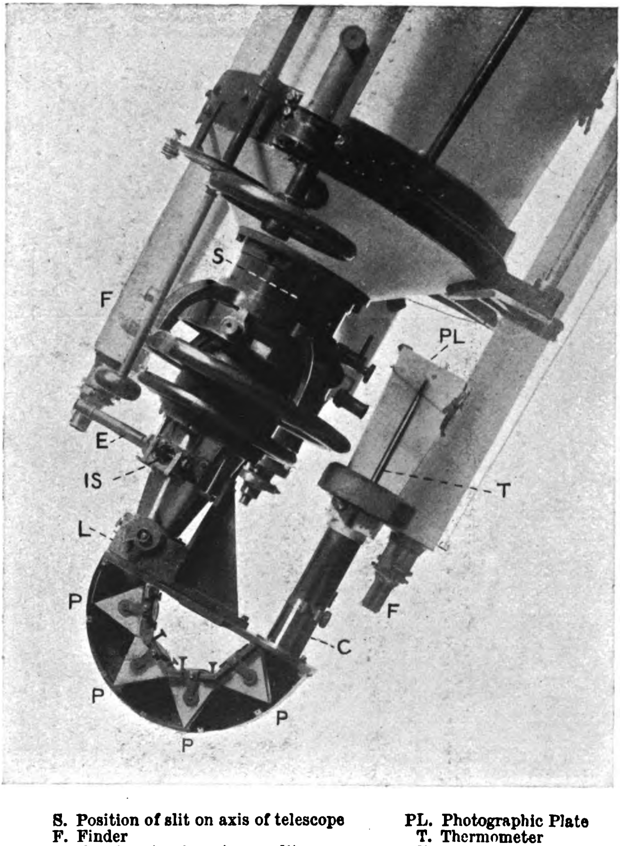
B. SOLAR SPECTRUM COMPARED WITH THE SPECTRUM OF AN IRON SPARK
(The region here represented is the same as in figure A above) *see* p. 65

PLATE II.



TYPICAL STELLAR SPECTRA (Secchi)

PLATE III.



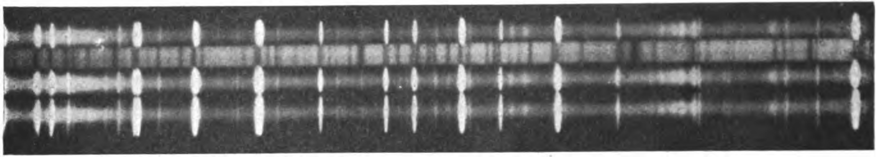
S. Position of slit on axis of telescope
F. Finder
E Eyepiece to view star on slit
IS. Iron spark
L. Lens of collimator

PL. Photographic Plate
T. Thermometer
F. Finder
C. Camera
P. Prisms

THE EYE-END OF A TELESCOPE WITH A STELLAR SPECTROSCOPE ATTACHED

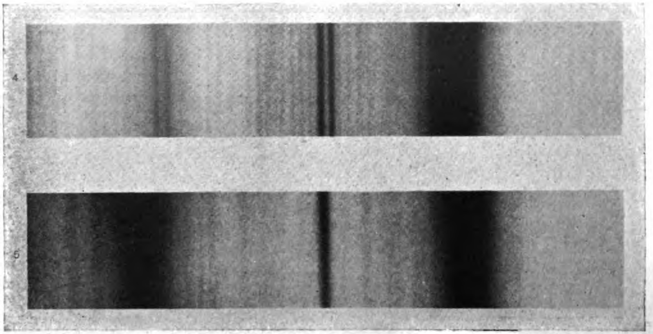
(Cambridge Observatory) see p. 89

PLATE IV.



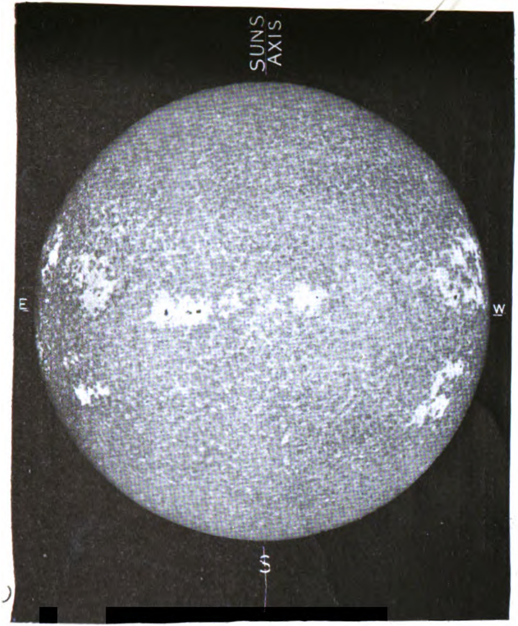
A. SPECTRUM OF α PERSEI WITH SPECTRA OF IRON SPARK (*see* p. 89)

Note that the stellar absorption-lines are shifted to the left of corresponding spark-lines, an indication that the star and the earth were approaching one another when the photograph was taken.

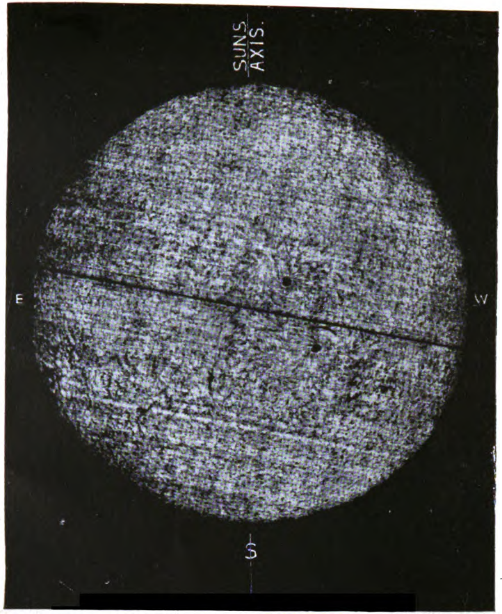


B. SPECTRA OF β AURIGÆ (*see* p. 91)

Plate V.



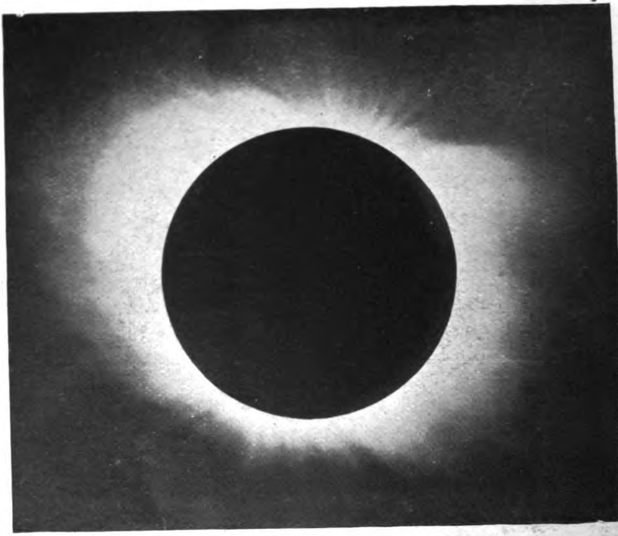
A. Calcium (Violet), July 22, 1906



B. Hydrogen (Red, H_a), October 7, 1908

THE SUN'S SURFACE PHOTOGRAPHED BY HALE'S SPECTROHELIOGRAPH SHOWING THE DISTRIBUTION OF CERTAIN GLOWING VAPOURS (*see* p. 98)

PLATE VI.



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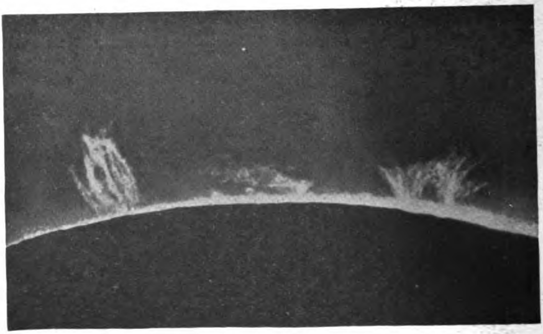
(The dark disc is the black body of the Moon eclipsing the bright surface of the Sun)



B. SOLAR PROMINENCES, PHOTOGRAPHED BY E. E. BARNARD DURING THE TOTAL SOLAR ECLIPSE, MAY 28, 1900 (*see* p. 103)

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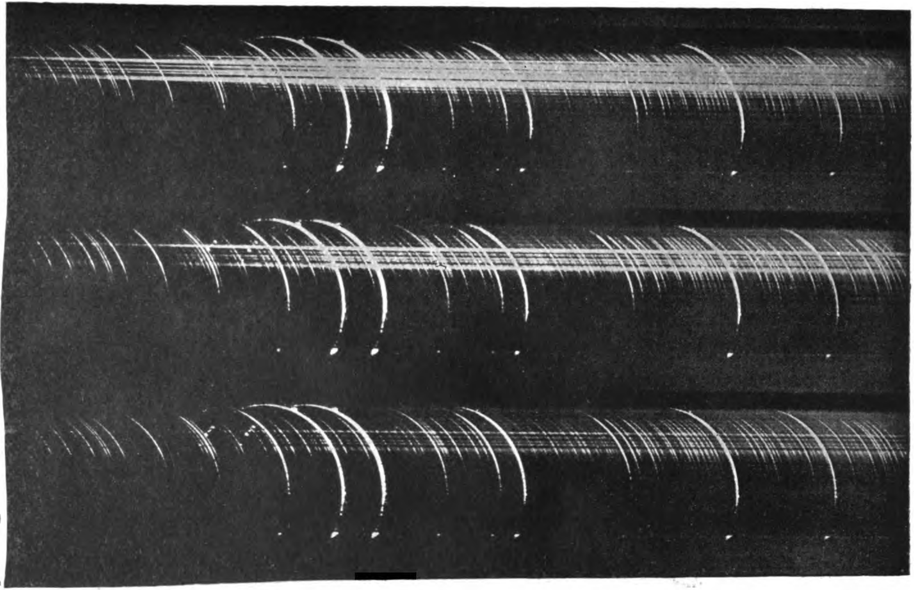
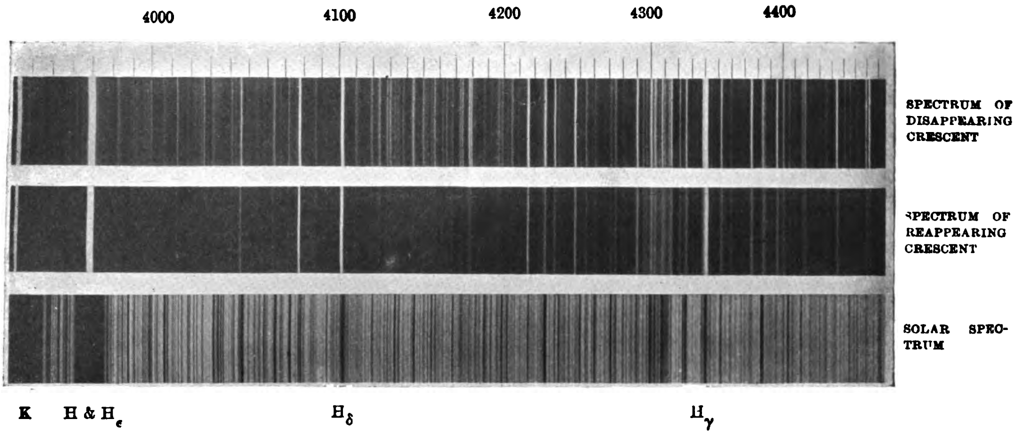


THE "FLASH" SPECTRUM OF THE SUN'S LIMB, IN FIRST MOMENTS OF A TOTAL ECLIPSE OF THE SUN (LOCKYER AND FOWLER IN INDIA, JANUARY 22, 1898) *see* p. 106

PLATE VIII.



SPECTRA OF THE SUN'S LIMB, BEFORE AND AFTER TOTAL ECLIPSE, COMPARED WITH THE ORDINARY SOLAR SPECTRUM (*see* p. 106). (MAJOR E. H. HILLS, IN INDIA, JANUARY 22, 1898)